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ANALYSIS OF ENERGY EFFICIENCIES AND SOURCE TRADESPACE IN AN A2/AD SEABASE-TO-SHORE OPERATION WITH AN ASYMMETRIC THREAT

by

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Cohort 311-152O

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This capstone project supported the mission of the United States Marine Corps (USMC) Expeditionary Energy Office (E2O) for development and assessment of solutions that increase the energy efficiency of USMC operations in an antiaccess/area denial (A2/AD) mission. Primarily, this study analyzed energy efficiency during USMC seabase-to-shore operations by developing an operational model to determine the best combination of connectors among all feasible combinations within the selected seabase. This capstone concluded that mission objectives for throughput and fuel consumption during operations could not be met in all scenarios by all connector combinations, and identified why certain combinations of connectors had better broad utility and operational effectiveness. The secondary objective of this study was the exploration of new and alternative energy generation methods that are employable by the USMC, which maximize energy efficiency of Marine air-ground task force (MAGTF) operations at the shore site. Evaluation criteria were used to investigate feasible alternative energy sources that could support the power generation of the MAGTF operations. This capstone concluded that alternative energy technologies, when combined with diesel-electric generators, helped reduce fuel consumption of the MAGTF operations, and identified their availability and effectiveness for meeting energy goals.

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ANALYSIS OF ENERGY EFFICIENCIES AND SOURCE TRADESPACE IN AN A2/AD SEABASE-TO-SHORE OPERATION WITH AN ASYMMETRIC THREAT

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Submitted in partial fulfillment of the
requirements for the degrees of

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ABSTRACT

This capstone project supported the mission of the United States Marine Corps (USMC) Expeditionary Energy Office (E2O) for development and assessment of solutions that increase the energy efficiency of USMC operations in an antiaccess/area denial (A2/AD) mission. Primarily, this study analyzed energy efficiency during USMC seabase-to-shore operations by developing an operational model to determine the best combination of connectors among all feasible combinations within the selected seabase. This capstone concluded that mission objectives for throughput and fuel consumption during operations could not be met in all scenarios by all connector combinations, and identified why certain combinations of connectors had better broad utility and operational effectiveness. The secondary objective of this study was the exploration of new and alternative energy generation methods that are employable by the USMC, which maximize energy efficiency of Marine air-ground task force (MAGTF) operations at the shore site. Evaluation criteria were used to investigate feasible alternative energy sources that could support the power generation of the MAGTF operations. This capstone concluded that alternative energy technologies, when combined with diesel-electric generators, helped reduce fuel consumption of the MAGTF operations, and identified their availability and effectiveness for meeting energy goals.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2/AD	antiaccess/area denial
AAV	amphibious assault vehicle
ACE	aviation combat element
AHP	Analytical Hierarchy Process
ALC	Alternative Landing Craft
ANOVA	analysis of variance
AOR	area of responsibility
ARG	amphibious ready group
BDA	battle damage assessment
BIC	Bayesian Information Criterion
C2	command and control
CAESR	Close, Assemble, Employ, Sustain, and Reconstitute
CAP	combat air patrol
CAS	close air support
CD&I	Combat Development and Integration
CE	command element
CFF	Call for Fire
CJCS	Chairman of the Joint Chiefs of Staff
CMC	Commandant of the Marine Corps
CONOPS	concept of operations
COTS	commercial off-the-shelf
DOD	Department of Defense
DOE	design of experiments
DOTMLPF-P	doctrine, organization, training, materiel, leadership and education, personnel, facilities, and policy
E2O	Expeditionary Energy Office
E2W2	Expeditionary Energy, Water, and Waste
EFFBD	Enhanced Functional Flow Block Diagram
EPF	expeditionary fast transport
FFBD	Functional Flow Block Diagram

FIFO	first-in-first-out
FOM	Free Orange Movement
GCE	ground combat element
GPM	gallons per minute
GPMD	gallons per Marine per day
HA/DR	humanitarian assistance/disaster relief
HQMC	Headquarters Marine Corps
ICD	Initial Capabilities Document
IED	improvised explosive device
INLS	Improved Navy Lighterage System
IPR	in-progress review
ISR	intelligence, surveillance, and reconnaissance
JCIDS	Joint Capability Integration Development System
JHSV	Joint High Speed Vessel
JIC	Joint Integrating Concept
JTF	joint task force
KPPs	key performance parameters
LARC-V	lighter, amphibious resupply, cargo-vehicle
LCAC	landing craftAir Cushion
LCAT	Landing Catamaran
LCE	logistics combat element
LCU	Landing craft, utility
LF	landing force
LFORM	landing force operational reserve material
LMSR	large, medium-speed roll-on/roll-off
LZ	landing zone
M&S	modeling and simulation
MAGTF	Marine air-ground task force
MANA	Map Aware Non-uniform Automata
MARFORCOM	Marine Forces Command
MARFORLANT	Marine Forces Atlantic
MARFORPAC	Marine Forces Pacific

MBSE	model based systems engineering
MCTL	Marine Corps Task List
MCTs	Marine Corps Tasks
MEB	Marine expeditionary brigade
MEF	Marine expeditionary force
MEU	Marine expeditionary unit
MLP	mobile landing platform
ModL	An ExtendSim programming language structured like C++
MOE	measure of effectiveness
MOP	measure of performance
MPEM	MAGTF Power and Energy Model
MPF	maritime pre-positioning force
MPTT	Mission Payload Transfer Time
MSR	main support routes
NCA	National Command Authority
NOLH	Nearly Orthogonal Latin Hypercubes
NPS	Naval Postgraduate School
OPLANS	operational plans
PK	Probability of Kill
PLC	Payload Capacity
POM	Program Objective Memorandum
POR	Program of Record
RPG	rocket propelled grenade
SAF	small-arms fire
SE	Systems Engineering
SEED	Simulation Experiments & Efficient Designs
SEF	South East Federation
SME	subject matter expert
SS	sea state
SSC	Ship-to-Shore Connector
SSD	Seabase Standoff Distance
STOM	ship-to-objective maneuver

TFU	Total Fuel Used
TLT	Total Loiter Time
UAV	unmanned aerial vehicle
UNREP	underway replenishment
USMC	United States Marine Corps
USN	United States Navy
USNR	United States Navy Reserve
USPACOM	United States Pacific Command
WARNORD	warning order

EXECUTIVE SUMMARY

As support costs increase while budgets decrease in modern military programs, the United States Marine Corps (USMC) and the United States Navy (USN) must find newer and more efficient means to carry out their missions. In recognizing an operations energy dependency and high energy cost, the Commandant of the Marine Corps (CMC), stood up the Expeditionary Energy Office (E2O). The purpose of the E2O is to "analyze, develop, and direct the Marine Corps' energy strategy to optimize expeditionary capabilities across all warfighting functions" (HQMC.Marines.mil 2009). The objective of the E2O and this project is to improve energy efficiency while maintaining mission effectiveness during a seabase-to-shore operation. As a secondary objective, this project studied the impact of substituting alternative and renewable energy sources for the traditional diesel generators currently used during shore site sustainment.

The following research questions provide the necessary framework to explore the energy efficiency of both the seabase-to-shore and shore site objectives:

1) How does the selection of seabase-to-shore connector type affect the throughput and energy efficiency of the seabase-to-shore operations of a STOM in an A2/AD threat environment?

2) What operational, tactical, and environmental factors have a statistically significant effect on the energy efficiency of the seabase-to-shore portion of seabase operations?

3) Which possible technologies will enhance energy efficiency, while maintaining operational effectiveness and success, during the sustainment phase of the operation?

To accomplish this objective and mission, the USMC and USN have established the concept of "seabasing." "Seabasing is defined as the deployment, assembly, command, projection, sustainment, reconstitution, and reemployment of joint power from the sea without reliance on land bases within the operational area. Seabasing incorporates the traditional naval missions of sea control, assuring access, and power projection with an increased emphasis on maneuver from the sea" (USMC CD&I 2015, 3). The overall seabase CONOPS encompasses all phases included in moving the joint task force (JTF)

from CONUS to the objective (OBJ). This CONOPS is divided into five distinct phases: Close, Assemble, Employ, Sustain, and Reconstitute (CAESR).

This project supports the assessment and selection of the best strategy to transport personnel and equipment from a seabase to a shore site while improving energy efficiency. Movement is carried out using a collection of specialized near-shore amphibious boats which are used as connectors from the much larger ships to the shoreline and can transition from deep water to the shore. The team developed a CONOPS for the movement of the landing craft, utility (LCU); the landing craft, air cushion (LCAC); and the Landing Catamaran (LCAT) to transport a Marine expeditionary unit (MEU)–sized MAGTF command element (CE), a ground combat element (GCE), and logistics combat element (LCE) to shore from a seabase and maintain these elements on the shore site. For this project, the team considered the mission complete when the transport of personnel and equipment from a seabase to a shore site was accomplished with minimal loss of life from local antiaccess/area denial (A2/AD) asymmetric threat, in a timely manner.

Recommendations from two previous capstone projects, Bourgeois et al. (2015) and Skahen et al. (2013), were used as the basis for this capstone project. This capstone project used relevant aspects of the A2/AD operational scenario provided by Bourgeois et al. and follows the recommendation provided by focusing further analysis on the Employ phase of the operation. Additionally, this capstone project draws from the conclusion of Skahen et al. and conducts a more detailed analysis of the STOM focused on the operation of the surface borne connectors only, rather than the seabase or the land connectors. Furthermore, at the direction of the E2O sponsor, this capstone project focused on the amphibious ready group (ARG) type seabase rather than a maritime pre-positioning force (MPF) type seabase, and simulated that seabase at distances of 12, 18, and 24 Nautical Miles (NM). Also significant within this study, were the A2/AD effects characterized by small-arms fire (SAF) machine guns, irregular infantry with rocket propelled grenades (RPGs), and defensive measures that include improvised explosive devices (IEDs) scattered along the coastline.

During the employment of troops in this capstone project's scenario, a sustainment operation must begin to support the personnel and equipment that is landed ashore. This sustainment effort continues through phases I and II of the Ship-to-Objective-Maneuver (STOM) scenario, concluding with the execution of the USMC mission objective and the commencement of the reconstitute phase. Viable alternative energies were then simulated in the MAGTF Power and Energy Model (MPEM) to obtain power generation capabilities for a three-day operational scenario. Wind, solar, wave, and hybrid technologies were assessed using the MPEM determine the feasibility and replaceability of their usage in the sustainment portion of the scenario.

Using the Marine Corps Task List (MCTL) and Marine Corps Warfare Publications (MCWP), the project team created key performance parameters (KPPs), measures of effectiveness (MOEs), and measures of performance (MOPs) to decompose and trace to during the development of a simulation model. This model was used to represent the seabase-to-shore movement using 27 distinct combinations of surface connectors that could realistically comprise a three-ship ARG. This project used design of experiments (DOE) to define the combinations of input factors to be investigated in the simulation model, exploring 27 combinations of connectors for seabase standoff distances (SSD) of 12, 18, and 24 NM and sea states (SS) of one, two, and three.

Three scenarios out of the 27 realizable scenarios for a three-ship ARG met the limits for all combinations off SSD and SD. These scenarios were as follows:

1) Scenario #6: 2 LCU, 2 LCAC, 4 LCAT

2) Scenario #21: 1 LCU, 7 LCAT

3) Scenario #27: 8 LCAT

One commonality that comprised all three scenarios was the LCAT which had performance parameters between the LCU and LCAC. This identifies the need for a hybrid connector that is faster than the LCU but has an energy efficiency superior to the LCAC. One of the reasons the LCAT was chosen for this study was because of the catamaran hull shape allowing for less drag and increased hull speed, resulting in a better fuel efficiency than the traditional hull types. The data suggests a platform with these

hybrid performance parameters would provide an advantage across the broad utility of missions required of U.S. Navy connectors.

Selection of shore site power alternatives were conducted using the analytical hierarchy process to rank the evaluation criteria and the energy sources being evaluated. The results of this process identified the top three alternative energies to be further explored for use during a three-day sustainment operation at the shore site. MPEM was used to determine the power demand of the Marine expeditionary unit (MEU) and the power generated by each alternative energy for a military grade, commercially available system selected by the project team. From this simulation, a data table was able to be compiled that identified the number of kilowatts (kW) per day that were produced. These numbers were then used to derive the number of alternative energy systems needed to produce enough power to meet USMC renewable energy goals. The result was that the Uprise Energy wind generator capable of producing 50kW and the FlexGen system from Earl Energy producing 35kW can meet 2016 renewable energy goals with a realistic number of systems.

This study yielded three primary conclusions:

Conclusion one: The mission objectives for throughput and fuel consumption could not be met in all scenarios by varying the combination of landing craft, utility (LCU) and the landing craft, air cushion (LCAC) alone.

Conclusion two: The introduction of an alternative intermediate-capability connector provided solution sets meeting all mission objectives.

Conclusion three: Alternative energy technologies, in combination with diesel-electric generators, can contribute to reducing the fuel consumption of MAGTF command element operations ashore.

The major conclusions drawn from the MBSE analysis conducted in this project indicate that an alternative intermediate-capability craft, such as the LCAT, may be critical in improving the energy utilization of the surface connector fleet while maintaining or improving mission effectiveness. Though numerous analysis-of-alternatives have been conducted in an attempt to provide direction to the acquisition

agencies, the research performed by the capstone team found no alternatives similar to the LCAT. With operational data readily available, it is recommended that the LCAT be evaluated against other connectors in an analysis-of-alternatives to determine whether it has the potential to be seriously considered as a replacement.

Additionally, the capstone report has shown the potential for alternative fuel technologies to subsidize diesel-based power generation to the levels sought after by USMC doctrine. Current E2O programs-of-record (POR) seem to be entirely based on solar power. It is recommended that the E2O further explore the use of hybrid energy storage based solutions like FlexGen or wind based solutions like the portable wind turbine developed by Uprise Energy as potential PORs to meet the growing power demand by alternative energy solutions in the battlefield.

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I. INTRODUCTION

For decades, the U.S. military has been performing the mission of an amphibious assault. This mission is one of the most critical functions performed by the U.S. military to enter both friendly and hostile countries from the sea. Over the course of time, this mission has evolved with the tactics employed by the military forces into what it is today.

One of the first and most iconic amphibious assaults was in World War II at the beaches of Normandy, when, according to U.S. Navy (USN) historians, the allied forces delivered between 130,000 and 156,000 troops in the first day. Over the course of the next month, one million troops were landed with approximately 150,000 vehicles and 110,000 tons of supplies (U.S. Navy 2015). Unlike the invasion of Normandy (Operation Neptune), large-scale invasions of countries are no longer feasible nor are they likely. Rather, the U.S. military has chosen to focus on the capability to deploy and recall troops all over the world, in a rapid fashion.

In this capstone project, the United States Marine Corps (USMC) and the USN will be cooperatively deploying forces from a grouping of ships called a seabase. Seabasing was introduced to mitigate and solve the issue of rapidly deploying and recalling troops worldwide. It allows the base of operations to become mobile and re-deployable by either using a group of traditional USN amphibious ships, called an amphibious ready group (ARG), or a group of specialized USMC/USN prepositioning ships called a maritime pre-positioning force (MPF). This approach results in several advantages and disadvantages for the USMC/USN. One of the traditional problems with amphibious operations is the supply chain that is required to enable the deployed personnel and equipment to function. These personnel and equipment require food, fuel, water, and many other recurring resources to operate. This “logistics tail” demands a constant flow of shipping by air, land, or sea and is costly to maintain for long periods of time. A benefit of this approach is that a seabase does not require the deployed force to transport all of the infrastructure equipment it might have otherwise required in an isolated situation.

The seabasing Joint Integrating Concept (JIC) introduced the term "Connector" and uses it to define "the surface and vertical lift platform capabilities that are critical to transport personnel, supplies, and equipment within the seabase and maneuver them from the seabase to the objectives ashore." Additionally, the JIC notes that, "Connectors are arguably the most critical capability possessed by any Seabase." (USMC CD&I 2015, 19). Throughout this capstone report the term connector refers to any vehicle or means of transporting personnel and/or equipment from the seabase to the shore or objective whether by air, land, or sea (surface or subsurface).

According to Dickey (2004), seabasing allows naval and joint forces to operate around the world without the prior establishment of permanent seaward ports and/or landward airports. Without permanent bases to sustain, seabasing no longer needs to maintain the same supply levels nor deliver supplies meant for extended sustainment to the shore site, but rather simply what is needed in the near term. Alleviating this supply burden enables the seabase to supply and sustain multiple simultaneous missions using unbounded land, sea, and air connectors as supply transport mechanisms. The seabase accomplishes this in a more mobile and flexible manner than previously possible. Dickey describes how a seabase is sustained by air and sea supply lines from strategically placed intermediary bases connected to the U.S. Finally, Dickey claims that "This system is capable of increasing throughput through the seabase if initial operations grow into sustained operations ashore requiring more forces, equipment and sustainment" (Dickey 2004, iii).

The USMC, for the past several years, has studied the "problem" of getting a force to its destination and then supplying that force. The USMC, in order to maintain maximum preparedness and adaptability, delivers essentially the same personnel and equipment to shore regardless of the mission. The USMC and USN forces customarily execute their mission at a worst-case manning level, with the full equipment loadout. The equipment delivered to the shore ranges from fuel and water trucks to excavation and paving equipment to ensure that ground forces are sufficiently supplied to support their mission.

A. PROJECT OBJECTIVES

The USMC and USN have recognized the need to transport troops, vehicles, supplies, and logistics support, hereinafter personnel and equipment, from a seabase to a shore site in a rapid and orderly fashion. They must then support those personnel and equipment by establishing a supply line that delivers all perishable and depletable resources to the force by land, sea, and air. The Commandant of the Marine Corps (CMC), in recognizing the reliance on energy in these operations, stood up a new office called the Expeditionary Energy Office (E2O). The purpose of this new office was to "analyze, develop, and direct the Marine Corps' energy strategy to optimize expeditionary capabilities across all warfighting functions" (HQMC.Marines.mil 2009). The USMC E2O contacted the Naval Postgraduate School (NPS) to research ideas that could improve the energy efficiency of the USMC operations while operating under an asymmetric antiaccess/area denial (A2/AD) mission.

The objective of the E2O and this capstone project is to improve energy efficiency while maintaining mission effectiveness. To assess that effectiveness, this capstone project studied the energy utilization of portions of a Ship-to-Objective-Maneuver (STOM) and provided recommendations for how to improve this mission area. Analysis of this mission area and exploration of this trade space required a modeling and simulation capability to identify a means of reducing associated total fuel consumption. A key component was to identify the best possible combination of the surface connectors that transport troops, equipment, and supplies from the seabase to the shore during the STOM, and the feasibility of using connectors fueled by alternative energies. The secondary objective was to analyze the shore site power demands of the landing forces. The stakeholders provided the Marine air-ground task force (MAGTF) Power and Energy Model (MPEM), which was used to complete this analysis. The MPEM already provided the capability to analyze power generation and consumption for a variety of personnel and equipment, but power generation capabilities focused on traditional diesel generators with very little focus on alternative energy solutions. Analysis of several alternative energy solutions and recommendations provided in this capstone report helps the E2O to meet its renewable energy goals.

B. QUESTIONS

The following research questions provide the necessary framework to explore the energy efficiency of both the seabase-to-shore and shore site objectives:

1) How does the selection of seabase-to-shore connector type affect the throughput and energy efficiency of the seabase-to-shore operations of a STOM in an A2/AD threat environment?

2) What operational, tactical, and environmental factors have a statistically significant effect on the energy efficiency of the seabase-to-shore portion of seabase operations?

3) Which possible technologies will enhance energy efficiency, while maintaining operational effectiveness and success, during the sustainment phase of the operation?

This study provides answers to these questions based on the insight gained through the Model Based System Engineering (MBSE) and modeling and simulation (M&S) efforts conducted. Research questions one and two look to evaluate combinations of seabase-to-shore connectors, with a focus on reduction of total fuel consumption for the STOM. While each connector provides a similar function, each has different connector specific performance parameters. This capstone investigated both throughput and fuel consumption to determine whether certain combinations of connectors employed during the STOM maximize energy efficiency while maintaining operational effectiveness. This analysis also identifies what performance parameters specific to each connector were critical to meeting mission success. Finally, the measures of performance (MOP) for the M&S effort are analyzed to determine the most statistically significant factors. These factors are further evaluated to identify how they can improve energy efficiency.

Additionally, question three looks to evaluate several alternative energy technologies, along with commercially available solutions, to implement energy efficiency goals during the sustainment portion of the operation. The approach is to provide a comparison of renewable energies and the number of these systems required to meet energy goals.

C. PROBLEM BACKGROUND

"Seabasing is defined as the deployment, assembly, command, projection, sustainment, reconstitution, and reemployment of joint power from the sea without reliance on land bases within the operational area. Seabasing incorporates the traditional naval missions of sea control, assuring access, and power projection with an increased emphasis on maneuver from the sea" (USMC CD&I 2015, 3). The overall seabase concept of operations (CONOPS) encompasses all phases included in moving the joint task force (JTF) from the continental U.S. (CONUS) to the objective (OBJ). This includes planning for the movement of troops, equipment, and supplies from CONUS aerial ports of embarkation (APOE) and seaports of embarkation (SPOE), either directly to remote aerial ports of debarkation (APOD) and seaports of debarkation (SPOD) or through the seabase and advanced land bases. This movement provides a coordinated response of force to meet the mission objectives. This CONOPS is divided into five distinct phases, Close, Assemble, Employ, Sustain, and Reconstitute (CAESR), which are graphically displayed in Figure 1. USMC CD&I defines CAESR as:

- Close: The closure of joint force capabilities to the area of crisis.
- Assemble: The integration of scalable joint force capabilities within the seabase.
- Employ: The employment of joint force capabilities from and supported by the seabase.
- Sustain: The sustainment of selected joint forces afloat and ashore across the Range of Military Operations.
- Reconstitute: The capability to recover, restore, and redeploy joint combat capabilities within the maneuverable seabase for subsequent operations. (USMC CD&I 2015, 4)

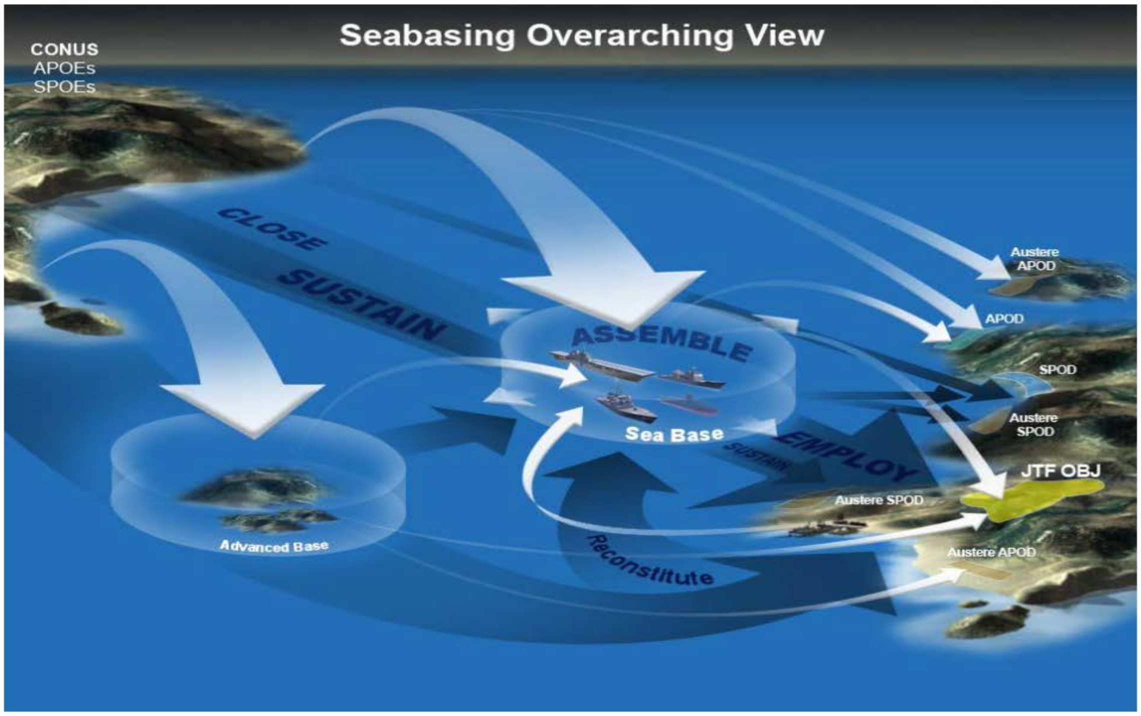


Figure 1. Elements of the CAESR Seabase CONOPS. Source: Brodie (2015, 5).

The analysis in this capstone report adds to the body of work conducted at the Naval Postgraduate School in support of the E2O efforts to maximize energy utilization throughout the seabase CONOPS. This work, in addition to previous capstone reports, includes analysis of the various phases of the seabase CONOPS to "provide commanders the information they need to drive efficiencies that translate into combat effectiveness" (USMC n.d.-b, 25). The USMC Expeditionary Energy Strategy also calls the USMC to integrate energy requirements into procurement and pursue emergent technologies to meet mid and long term needs as a part of their Expeditionary CONOPS (USMC n.d.-b 25). Previous capstone projects conducted at NPS have focused on the Close phase and portions of the Employ phase which are describe in the Chapter II. This capstone project focused on the seabase-to-shore movement of the Employ phase of the CONOPS only, specifically on the operation of the surface borne connectors. Connectors are deployed during the Employ phase to land the initial personnel and equipment, during the

Sustainment phase to deliver supplies, and during the reconstitute phase to recover anything deployed during the previous two phases.

Each type of connector has unique operational characteristics and tactical capabilities, as well as specific interface modes and requirements at both the shore and seabase. The correct mix of connector types is highly dependent on the unique operational considerations of a given landing force (LF) CONOPS. Commanders select the mix and employment of connector types based on the tactical considerations of the LF CONOPS; however, they have limited information or ability to consider the energy use implications of these selections.

Airborne connectors provide numerous options for maneuvering cargo from the seabase to the shore. These connectors can reach further inland and operate at greater speeds than their surface connector counterparts. Airborne connectors are often used to "supplement the landing craft in the off-load of high-priority and emergency resupply items" (Chairman of the Joint Chiefs of Staff [CJCS] 2014, III-22). Surface borne landing craft, however, comprise the principal heavy lift offload capability for LF equipment and supplies (DoN1 2004, 3–2), and are responsible for the largest portion of tonnage throughput of the seabase-to-shore movement. Airborne and surface borne connectors have different principal factors that influence their tactical and energy performance. An analysis encompassing both connector types has the potential to be too complex or too general to yield meaningful insight to the selection of particular craft type within each category. As a result, this capstone project focuses on the operation of the surface borne connectors specifically. The research questions and analysis were structured to improve the stakeholders' understanding of the trade space between tactical effectiveness and energy efficiency in selecting the mix of surface borne connectors in the execution of the seabase-to-shore movement.

D. METHODOLOGY AND SCOPE

This capstone project supports the assessment and selection of the best strategy to transport personnel and equipment from a seabase to a shore site while improving energy efficiency. Movement is carried out using a collection of specialized near-shore

amphibious boats, which are used to connect (i.e., connectors) the much larger ships to the shoreline and can transition from deep water to the shore. The boats currently in use have evolved since the earliest amphibious landings. Some, like the Landing craft, utility (LCU), have been in service since World War II while others, like the landing craft, air cushion (LCAC), have only been in service since the 1980s. More recently, the USN has commissioned several projects to research replacements for both the LCU and the LCAC. The Ship-to-Shore Connector (SSC) program is currently set to replace the LCAC, and an "LCU Replacement" program has been underway for the past several years. Other alternatives created by foreign militaries have also been explored, including a vessel that converts from a catamaran to a flat bottom boat called a Landing Catamaran (LCAT). With this in mind, the team developed a CONOPS for the movement of specialized near-shore amphibious boats, such as the LCU, LCAC, and LCAT, to transport a Marine expeditionary unit (MEU)–sized MAGTF command element (CE), hereinafter CE, as well as the supporting ground combat element (GCE) and logistics combat element (LCE).

For this capstone project, the team considered the seabase-to-shore mission complete when the transport of personnel and equipment from a seabase to a shore site was accomplished with minimal loss of life from local asymmetric threat in a timely manner. The primary objective of this project was to analyze energy efficiency of the seabase-to-shore operations while maintaining the overall operational and mission effectiveness. Specifically, a tailored systems engineering approach was used by the team to perform a trade-off analysis between the total fuel consumption, total time to complete the seabase-to-shore operations, and feasible combinations of specialized near-shore amphibious boats. The team developed a simulation model to perform a trade-off analysis for the seabase-to-shore operations.

In addition to the transport of personnel and equipment, the initial sustainment for the mission was explored as a secondary objective. Once on shore, a CE requires services to sustain the personnel and equipment at the shore site. As a result, this capstone project effort investigated the integration of renewable energy sources (i.e., wind turbines, solar cells, FlexGen systems, wave attenuators, and point absorbers) into the existing solutions

(i.e., diesel generators) at the shore site. The team used an Analytical Hierarchy Process (AHP) as an assessment tool to evaluate and identify feasible alternative energy sources that could support the power generation at the shore site. The capstone team also conducted a study on whether current technologies could produce the power required to replace or augment the current configuration.

In summary, this capstone project focused on the development of an extensive, repeatable, expandable, and portable tool as well as a methodology for the analysis of the seabase-to-shore operations. Specifically, the seabase-to-shore operations were the primary objective of this effort. Additionally, this effort explored new and alternative methods and tactics that are employable by the USMC, which maximize energy efficiency of MAGTF CE operations at the shore site. Finally, this capstone project explored the feasibility of a new specialized near-shore amphibious boat for the seabase-to-shore operations based on the usage of alternative fuels/energy.

E. STAKEHOLDERS

The stakeholders involved in this capstone project included the E2O and the expeditionary Marines Corps. The E2O was the key stakeholder whose primary goal is to "ensure that the Marine Corps will forever remain most ready when the Nation is least ready, by creating a lighter, more efficient force that goes farther and stays longer on every gallon of fuel we use" (Amos 2013, 1). The E2O is committed to this goal and continues to search for recommendations fortified by formal SE practices and analysis. With this goal in mind, the capstone team developed a model that represents the energy utilization of a STOM mission and scenarios that explored variation in feasible STOM strategies bound by a three-ship ARG.

Two key objectives of the E2O are to improve energy efficiency of the Marine expeditionary force and to reduce force dependency on fossil fuels. The capstone team obtained stakeholder guidance on mission areas of greatest interest for this study as well as available tools for use/reuse. The team explored energy efficiency strategies for STOM mission execution and MAGTF CE operations ashore in order to develop measures, requirements, functions, and scenarios that meet the stakeholder needs. A series of

models were created to simulate STOM scenarios and output data in support of this study. The scenarios were proposed to the stakeholders and then updated to set clear objectives for the research. In addition, tools such as Imagine That's ExtendSim, the USMC provided MPEM, and SAS Institute's JMP Pro were presented and approved for use during the analysis.

II. INITIAL RESEARCH, ASSUMPTIONS, AND DECISIONS

This chapter focuses on the initial research, decisions, and assumptions that impacted the capstone project's scope and processes. The ship-to-objective maneuver (STOM) effort ensures that a Marine air-ground task force (MAGTF) can gain forcible entry and close on an objective inland. The overall maneuver from the seabase is a complex evolution that includes multiple connector types, a diverse set of operating forces and logistics support, and multiple phases. Many aspects of this overall maneuver have been analyzed in a broader scope in previous capstone projects. In an effort to complement and extend this existing body of work, two previous capstone projects in particular were selected to be built upon. The initial research also included selecting either the amphibious ready group (ARG) type or maritime pre-positioning force (MPF) type major seabase form factors and making several assumptions to simplify the model. These decisions were critical to the capstone team's ability to properly scope what to accomplish in the length of a capstone project. The capstone team did not have enough information to make some of decisions, and therefore required stakeholder guidance on these decisions. Where possible, the capstone team made assumptions that either distilled the effort down to only include the most impactful elements, or reduced the scope to an achievable level for this capstone project.

A. PREVIOUS CAPSTONE PROJECTS AND THESES

In their capstone project, Bourgeois et al. (2015) studied the Close phase and examined the effects of augmenting traditional amphibious navy shipping with faster, more efficient commercial shipping as an alternative means to reduced fuel consumption. The authors analyzed shipping alternatives to support a Marine expeditionary brigade (MEB) in A2/AD and humanitarian assistance/disaster relief (HA/DR) scenarios. The mission, based on Expeditionary Warrior 2012, occurred in a location within the U.S. Pacific Command (USPACOM) area of responsibility (AOR) where an evolving instability in the fictitious allied nation of Orange was used as the context for the analysis. Bourgeois et al. provided two relevant conclusions for this capstone to build on;

that “A2/AD and HA/DR missions were most influenced by sea state and the number of ships sailing, when considering fuel consumption,” and that “further investigation into the effects of augmented shipping on the Assembly and Employ phases of seabasing operations” would be beneficial (Bourgeois et al. 2015).

In another capstone project, Skahen et al. (2013) explored various combinations of both air and surface connectors in moving a Marine expeditionary brigade (MEB) sized force from the seabase to the shore during both the forcible entry and sustainment portions of the STOM in an A2/AD environment (Skahen et al. 2013). The capstone project used a stochastic model of the surface and air connectors to analyze the effect the seabase and beach support on the time required to complete the operation and the fuel used. The capstone project’s findings included: that “increases to seabase distance and sea state significantly increased both the time to complete the operation and the fuel used during the operation” and that when “adverse conditions exist, the LCU may be able to provide better fuel economy over employment of the LCAC.” Additionally, the study concluded that “LCAC also had the most positive effect on performance of the Amphibious Assault mission, thus its employment should be considered judiciously when favoring payload throughput vs. fuel efficiencies” (Skahen et al. 2013).

These two capstone reports were chosen as the basis for this investigation to augment the NPS portfolio of E2O capstone reports. This capstone project used relevant aspects of the A2/AD operational scenario provided by Bourgeois et al. and follows the recommendation provided by focusing further analysis on the Employ phase of the operation. Additionally, this analysis draws from the conclusion of Skahen et al. and conducts a more detailed analysis of the STOM focused on the operation of the surface-borne connectors only, rather than the seabase or the land connectors. This approach allows the analysis to focus on the operation of specific connector types and the unique factors influencing their operation in the overall mission. The analysis focuses on the details of the craft interactions at the seabase and landing zones, and assesses the mission and environmental factors that have the greatest effect on fuel utilization and throughput.

Based on the results and recommendations of these previous capstone reports, as well as guidance from the E2O Sponsor, the problem statement for this capstone project was established:

> The United States Marine Corps must transport troops, vehicles, supplies, and logistics support from a seabase to a shore site in a rapid and orderly fashion. They must then support these personnel and equipment by establishing a supply line that delivers all perishable and depletable resources to the force by land, sea, and air. The mission is effective when the transport of troops, platforms, supplies, and logistic support from seabase-to-shore is accomplished with minimal loss of life. The purpose of this capstone project is to increase the energy efficiency of the operations while maintaining this operational/mission effectiveness.

B. DECISIONS FOR THE CAPSTONE PROJECT

As commonly experienced in Systems Engineering, problems often have multiple potential solutions and require decisions or direction to guide the solution space into the most desirable outcome. Along with higher level decisions, requirements decomposition inherently provides Systems Engineers the opportunity to make minor decisions that ultimately impact the final solutions to the problems being solved. The capstone team relied heavily on the available published guidance to direct how and where the study came to be. The stakeholders were contacted and guidance was received on all decisions that could not be made by the team itself. The capstone advisors were also consulted to provide course correction based on knowledge of the previous capstone projects and interactions with the wider community. Table 1 illustrates the requirements traceability of these decisions and the direction received throughout the capstone project. Sections one and two provide details on every notable decision made by the capstone team or decided/directed by the stakeholders.

Table 1. Requirements Traceability

Capstone Project Direction	Direction Provided by:	How Implemented
"Increased military capability gained through dramatic savings in weight and fuel transported" (USMC E2O n.d.)	E2O Mission and Vision	Evaluation of best combination of connectors to get from the seabase to the shore
		Evaluation of alternative energies to meet USMC energy goals
"Deployment and support of an expeditionary force" (NPS 2016)	capstone project overview	M&S focused on the seabase-to-shore effort
"Antiaccess/area denial (A2/ AD) with a non-traditional threat" (NPS 2016)	capstone project overview	Implementation of A2/AD threat in seabase-to-shore M&S
Use of a Marine Expeditionary Unit (MEU) (NPS 2016)	capstone project overview	MEU transported from the seabase to the shore
		MEU used for shore site power demand
Seabase Standoff Distance (SSD) of 12–18-24 NM	Col. Magnuson	SSD implement in M&S
Utilization of three-ship Amphibious Readiness Group (ARG) for the seabase	Col. Magnuson	ARG implemented in M&S
Something must be accomplished at the shore site	Col. Magnuson	Sustainment portion of capstone project was added for shore site

1. Sponsor Decisions

Only two major sponsor decisions were made during the capstone project effort. The first decision was to limit the SSD to three static distances, 12, 18, and 24 nautical miles (NM). This SSD was identified by the sponsor as an operational range of interest rather than a larger SSD, as has been selected in past capstone projects. Seabase Standoff Distance (SSD) is an important factor in any operational scenario, and therefore was considered a critical piece of information to the capstone project's models and simulations. The SSD is affected by the current threat and its capabilities to determine how far the seabase should remain from shore to mitigate any weapons that could be used

against it. The capstone team found that during many operations, the SSD is varied according to the current mission of the seabase. For instance, the distance is lowered during an amphibious landing (Employ phase), but during the Sustainment phase the distance is often increased to mitigate threat munitions impacting the seabase. Maintaining the SSD at 12–24 NM, consistent with sponsor guidance, had the added benefit of providing large open water transit distances, which amplified the differences in craft characteristics and provided more discrete simulation results. The team further assumed amphibious assault vehicles (AAV) could be omitted from the analysis due to this SSD exceeding the typical AAV swimming range. This decision also aligned with this capstone project's expansion of the previous capstone projects, which reduced SSDs to minimize connector effects while studying land connectors and seabase operations.

The second sponsor decision was whether to model a MPF type seabase, or the more traditional ARG type seabase. An ARG is made up of In-Service USN Amphibious platforms, or "L-Class" ships. A typical ARG is made up of a single Landing Helicopter Dock (LHD), Dock Landing Ship (LSD), and an Amphibious Transport Dock (LPD [landing platform/dock]) type ship, but can be augmented and modified to include any USN Amphibious Platforms dependent on the mission and discretion of the Fleet Commander. MPFs are a recent capability addition to the seabase architecture, combining existing sealift assets and purpose built vessels to facilitate the selective offload of a MAGTF in-theater. Elements of the MPF are shown in Figure 2.

Mobile landing platform (MLP) moored with large, medium-speed roll-on/roll-off (LMSR) (left), auxiliary dry cargo ammunition (T-AKE) (top right), expeditionary fast transport (EPF) (bottom right).

Figure 2. Ships of the Maritime Pre-positioning Force. Source: USMC CD&I (2015, 12, 15, 17).

The MPF architecture includes multiple ship types with various ship-to-ship and ship-to-connector interfaces required to execute a ship-to-shore maneuver. Figure 3 illustrates an overview of connector and ship interactions meant to highlight the increased complexity and modeling detail required to capture the interactions associated with a MPF rather than an ARG constituted seabase. Presently, an MPF seabase can only support LCAC operations through its mobile landing platform (MLP) interfaces. It requires the additional support of a conventional dock ship to conduct LCU operations. The sealift vessels within the MLP also dictate the nature of the cargo that can be supplied to the connector. For example, a large, medium-speed roll-on/roll-off (LMSR)/MLP combination can supply large quantities of rolling stock and cargo, but has a limited troop deployment capacity of approximately 100150 embarked troops. While an expeditionary fast transport (EPF)/MLP combination can debark more than 300 troops, has approximately one twentieth the cargo volume of an LMSR, and its rolling stock debarkation capability is limited by sea state restrictions on the EPF stern ramp.

Additionally, in many sustainment scenarios the solid cargo required to flow through the MPF seabase is delivered by a vertical replenishment interface with a supporting T-AKE. A substantial amount of modeling effort over the ARG would have been required to capture these details accurately. A tradeoff analysis was conducted to consider the model scope against the additional insight gained by adding alternative seabase architectures. Ultimately, the E2O sponsor provided direction and a decision at the second in-progress review (IPR) to continue the capstone project using an ARG type seabase (E2O 2016).

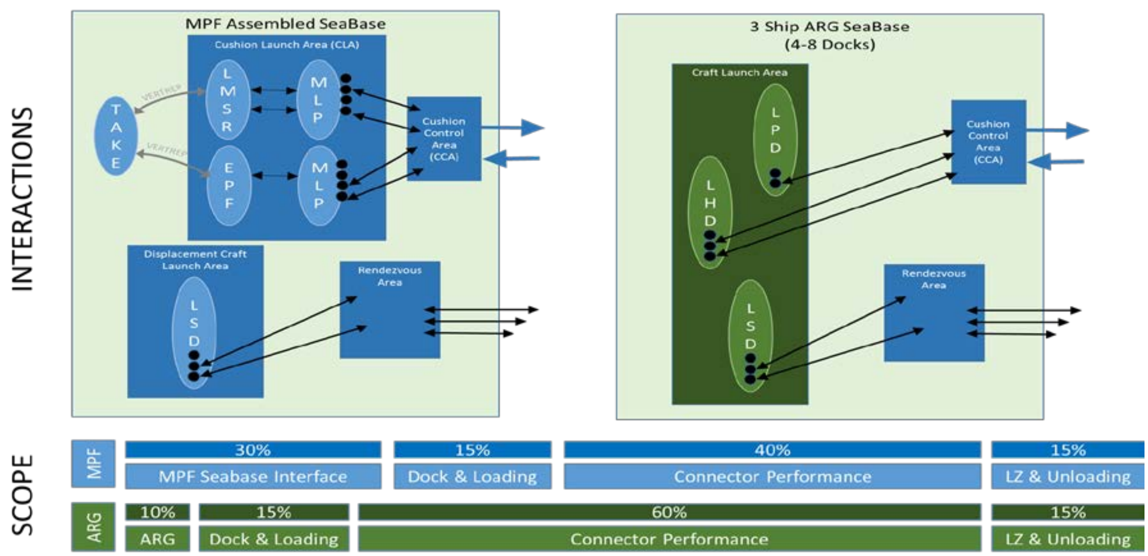


Figure 3. MPF Verses ARG

2. Capstone Team Decisions

Based upon the research and the preponderance of data, three separate landing craft types were selected for the analysis: the landing craft, utility (LCU) and the landing craft, air cushion (LCAC) shown in Figure 4, and a third conceptual craft represented by the prototype Landing Catamaran (LCAT). The LCU and LCAC represent the primary existing MC heavy-lift cargo connectors employed in seabase-to-shore off-loading operations. These two connectors have significantly greater lift capability than other amphibious and air connectors within the seabase, and are critical to the buildup of combat capability ashore during amphibious operations. The two craft have significantly different performance and cargo capacity characteristics. The primary advantages of the

LCAC over the LCU are its greater transit speeds, its ability to access a greater variation of landing sites, and the ability to traverse overland to debark cargo and troops “feet dry” ashore. The primary advantages of the LCU over the LCAC are the LCU’s approximately two and one-half time greater lift capacity, greater troop lift capacity, larger cargo deck area, longer sustained operation without refueling, and a significantly lower fuel consumption rate. The LCAT is an innovative variable draft craft that represents an intermediate capacity with performance characteristics that trade-off the higher lift and fuel efficiency of the LCU with the higher speeds of the LCAC lift. The LCAT has been in operation since 2012 and has conducted training exercises with U.S. amphibious forces including a successfully well-deck interface with USS Wasp (LHD 1) during Exercise Bold Alligator (CNIM 2016).

Figure 4. Landing Craft, Utility (LCU) (left); Landing Craft, Air Cushion (LCAC) (right). Source: USMC CD&I 2015, 19.

The LCU is a conventional displacement landing craft and has the highest lift capacity of the existing seabase connectors. The LCU has a single bow ramp for loading and unloading wheeled, tracked, and bulk cargo, and is capable of accommodating large numbers of troops on-deck. The LCU is capable of operating independently with a nominal amount of armored protection for the embarked troops and vehicles, and has survivability features built into the hull and critical systems. The LCU is versatile and economical to operate with a fuel burn rate of only 26 gallons per hour at full power. The disadvantages of the LCU are its relatively slow maximum speed and its fixed draft

restricting access to some beach unloading zones, often requiring troops and cargo to be to unload in the surf zone.

The LCAC is an amphibious hovercraft capable of high sustained speeds in moderate sea states. Its ability to hover and traverse overland make it capable of accessing “more than 70 percent of the world’s beaches, compared to 17 percent for displacement landing craft” (USMC CD&I 2015, 19). The LCAC is equipped both bow and stern ramps for drive-through loading and unloading of wheeled and tacked cargo. The LCAC troop carrying capacity is limited by the high spray environment on deck during transit, and therefore requires troops be sheltered in the interior cabins, or in erectable shelters on deck. While the LCAC is configured with deck shelters, it has limited ability to carry additional bulk or wheeled cargo. The LCAC’s fuel burn rate, which is highly dependent on cargo and environmental factors, can exceed 1000 gallons per hour at maximum power.

The Landing Catamaran (LCAT), shown in Figure 5, was used as a reference vessel for the purpose of introducing an alternative intermediate capability craft into the analysis. The LCAT uses a variable geometry hull form to convert from a shallow draft landing craft to a deeper draft catamaran with better open water resistance and seakeeping characteristics. A vertically adjustable cross-deck is lowered into the water to increase buoyancy in the landing mode and is lifted out of the water to convert to a deeper draft multi-hull for open water transit. The LCAT has a single bow ramp for loading and unloading wheeled, tracked, and bulk cargo. The LCAT has a fuel burn rate of 360 gallons per hour at full power (CNIM 2016).

Figure 5. Landing Catamaran (LCAT). Source: CNIM (2016).

C. ASSUMPTIONS

The capstone team made several assumptions to simplify the scenario for modeling purposes and to encourage significant results within the model. Assumptions were required to constrain the STOM model to complete the analysis. The assumptions are listed in order of significance from most to least. The most significant assumptions were required to address capability gaps in the STOM model and focus the M&S effort.

The first simplifying assumption was to eliminate the aerial vehicles from the model and only use them in a close air support/combat air patrol (CAS)/(CAP) situation that did not factor into the model's fuel usage. The model implemented surface connectors only which allowed the capstone team to focus on the tactics and usage of these connectors. As in previous capstone projects, an assumption was made that the threat and mission did not require greater than a single Marine expeditionary unit (MEU) to complete. In addition, any future use of the scenario and M&S artifacts could simply be rescaled to fit MEBs or Marine expeditionary forces (MEFs). Floating dumps for on-

call reinforcement of supplies and ammunition could have accounted for a measurable portion of surface connector capacity; however, they typically support larger MEB or MEF deployments. Based upon the MEU assumption, the team further assumed floating dumps would not be employed in the scenario analyzed.

1. Assumptions with Significant Impact on the Study

A single MEU-sized Marine air-ground task force (MAGTF) ground combat element (GCE) ashore is adequate to address the anticipated asymmetric threats and size of the opposing forces. If a larger force is needed, the study results could then be easily scaled up to provide movement of a larger force. A MAGTF CE in support of this MEU will be set up on shore to establish a base of operations for command and control (C2) of the MAGTF personnel and equipment transferred ashore. The MEU MAGTF platforms and equipment will consume fuel at a nominal rate during operations at the shore site in order to set a fuel consumption expectation without considering extreme environmental conditions, operational setbacks, or varying operational tempos.

Sea surface connector operations are executed while sea state is three or less. A fuel consumption rate was correlated to each of three surface connector power states so the study could be completed. The power states used in the STOM model are Off, Idle, and Full Power, and are assumed to be sufficient to execute the STOM. The connectors consume no fuel while in the *Off* state which is used while in the well-deck of an ARG ship, during mission module upload, and during refueling. The *Full Power* state is used when the connector is traveling to or from the landing zone (LZ), and consumes fuel at the maximum rate per the connector type regardless of payload weight. The *Idle* fuel state is used while the connector is at the LZ or loitering due to an A2/AD event or well-deck availability. Two different *Idle* states were developed for the LCAC to define fuel consumption while the connector was on or off cushion.

As discussed in Chapter II.B the stakeholders directed that an ARG type seabase be used. This capstone project further assumed that a three-ship ARG configuration could be used and that the aviation combat element (ACE) would operate from the seabase. Along with the elimination of ACE connectors, the three-ship ARG constrained the

quantity and combination of surface connectors used to execute the STOM mission within the ARG well-decks. The ARG was preferred because the amount of data and information available was ample to complete this baseline study and was selected by the stakeholder at our second in-progress review (IPR). Along with the seabase configuration, Seabase Standoff Distance (SSD) was the last key assumption critical to the study. Three SSDs of 12 NM, 18 NM, and 24 NM were provided and subsequently analyzed in the model. Though the standoff distances were directed by the stakeholders, these distances were assumed to correlate with actual ARG operations and validated the outputs of the STOM model.

2. Assumptions with Moderate to Minor Impacts on the Study

This study does not explore the implications of Blue Force attrition, either on the ground, or during the transfer. If a platform were to be destroyed or damaged, it could have significant implications to the end goal of this effort, but would not provide a controllable scenario with which to properly evaluate energy consumption. As such, probability of kill (Pk) and the effects of battle damage were not explored in our STOM model. All surface connectors are assumed to be available throughout the STOM mission and do not incur any damage due to A2/AD events or harsh environmental conditions.

The capstone team also assumed that mission modules with high packing density, such as the M1A1, uploaded faster than mission modules with lower packing density such as the landing force operational reserve material (LFORM), which require fork lift loading. The STOM model also implemented a variable control factor with an arbitrary 20% increase in loading rate to explore impact on STOM mission fuel consumption and impact on loading times. The loading rate variation affected both mission module upload time at the well-deck and download time at the LZ. The surface connector download times were set to one half of the connector upload time. The capstone team assumed surface connector Payload Capacity (PLC) was reduced in some cases due to the packing density calculated for each mission module. These calculations resulted in mission module loads with decreased payload weights but the surface connector deck areas were at capacity. The STOM model also implemented a variable PLC limiter control to explore

the relationship between payload weights and their impact on fuel consumption. However, without power curves that correlated to mission module load weights, the model used the full power state to transfer all loads to shore. The PLC limiter control had a range of 50% to 100% payload capacity in 10% increments.

The A2/AD threat environment simulated by the STOM model required Call for Fire (CFF) events that triggered Combat Air Support (CAS) or combat air patrol (CAP) missions. ACE response time was accounted for in the STOM model; however the fuel consumed by the ACE platforms was excluded from fuel use calculations within the model.

The model implements a First-In First-Out (FIFO) queue without considering mission module load matching to an optimal surface connector type. This simplified approach dictated that the first connector to arrive at the seabase would enter an available well-deck and upload a remaining portion of the mission module being transferred to shore. The mission module portion was assumed to be ready and incurred loading times consistent with other portions of the current mission module being transferred. The surface connectors returned with little to no payload weight (deck area is empty) and were directed to any ship in the ARG with a load ready for uploading. If all well-decks were busy when a connector arrived at the seabase, the connector loitered in a fuel saving power state until a well-deck became available. Well-deck availability (loiter time) varies based on surface connector counts participating in the STOM mission and the number of well-decks provided by a three-ship ARG. Overloading was identified during the course of research and was assumed not within the scope of this study.

The capstone team assumed surface connectors refueled concurrently during upload at the ARG only, therefore neither surface connector underway replenishment (UNREP) of fuel during transfer nor fueling at the LZ were not implemented in this STOM model. Refueling time did not exceed upload time and had no impact, though the refueling rate of 300 gallons per minute (GPM) was included in the throughput calculations. Surface connectors commence full of fuel and were preloaded for the first convoy (initial surge) prior to starting the STOM mission. There were no fueling delays incurred during the preloading of the surface connectors.

The A2/AD RPG event was defined in agreement with the principles of asymmetric warfare in a non-traditional environment using non-traditional threats. A uniform pseudo-random integer was used to trigger an RPG launch with a probability of occurrence equal to 2%. The RPG threat was assumed persistent and could occur during the STOM mission anytime a surface connector was within 1000m of shore. The launch of an RPG resulted in no damage to the surface connectors but did cause a five-minute loiter penalty in an idle power state so the surface connector under attack could return fire and mitigate the threat. In this case, the LCAC would remain “on cushion” but minimize thrust for propulsion while returning fire. The LCU and LCAT both kept the connector propulsion in gear to allow for positive steering control.

The A2/AD improvised explosive device (IED) event had a 100% probability of occurrence when the input factor was enabled. This event was programmed to occur once during the initial convoy only. If an IED threat was known to exist at the LZ, the surface connectors would loiter and launch IED countermeasures at a distance of 300m from shore and wait two minutes while the blast debris settled.

The A2/AD SAF event had a 100% probability of occurrence when the input factor was enabled. This event was programmed to occur once during the initial convoy only. When a SAF event occurred, the surface connectors stop 3000m from shore, perform a CFF and loiter for 15 minutes while the CAS aircraft returned fire and cleared the LZ of threats.

Each of the preceding assumptions had a different impact on the model and were used as defined. If the assumptions stated are no longer true, re-evaluation of the model will need to done ensure any changes do not cause a significant effect. The effects of these requirements impacted the model and DOE results. Any error in these assumptions will affect the results of the M&S effort.

D. SYSTEM ARCHITECTURE DEVELOPMENT

Defining and validating the problem was a vital function performed early in the project. Defining a problem can itself be problematic, but it is a singularly critical activity to project success. This capstone project started with several examples of well-defined

problems from previous capstone projects, helping to build a clear understanding of the problem early. The common context for this and the previous capstone projects was the analysis of operational and energy effectiveness in the execution of sea-based expeditionary maneuvers. The team, through understanding and addressing the problem statement, developed a functional architecture to capture the overall functions the MEU performs during its missions. After creating the overall hierarchy these functions were decomposed. Through this decomposition, relationships between elements, inputs, and outputs were added to the architecture. The software tool called Vitech CORE organized and managed this architecture. In the CORE software nomenclature, functions are titled with the letter "A" and components are titled with the letter "C," similar to IDEF0. In this chapter, the system architectures represent the hierarchical functions, the specific components that perform those functions, and the relationships between the two. The relationships between the components and functions can be seen in the EFFBDs; however, due to the embedded software rules, only one relationship can be assigned per function. The names of the components are used to create the relationship to the functions and can be found under each function block.

In order to relate the idealized behavior modeled in the simulation to actual mission functions, a hierarchical structure was created to capture both efforts. As shown in Figure 6, there are two top-level functions that address the project and USMC needs. The "Perform USMC Expeditionary Operations" function helps to construct an appropriate functional architecture for the proposed transportation system, and the "Perform USMC Expeditionary Simulations" function builds an analytical simulation that allows for operational analysis of the performance of the Expeditionary Operations function. The USMC Expeditionary Simulations emulate the functions performed by the USMC Expeditionary Operations and are closely correlated. The main difference being the simulation architectures also capture the activities relating to M&S functions. These architectures were used to define the sequences of events modeled in the simulation analysis. The process of creating the "Perform USMC Expeditionary Operations" functions helped identify any missing or omitted functions in the model and became a guide to complete the simulation functions. A detailed description of the Perform USMC

Expeditionary Operations function, and its sub functions are found in Chapter III, while a detailed description of the Perform USMC Expeditionary Simulations function and its sub functions, as well as a description of the development and use of the operational simulation, are found in Chapter IV.

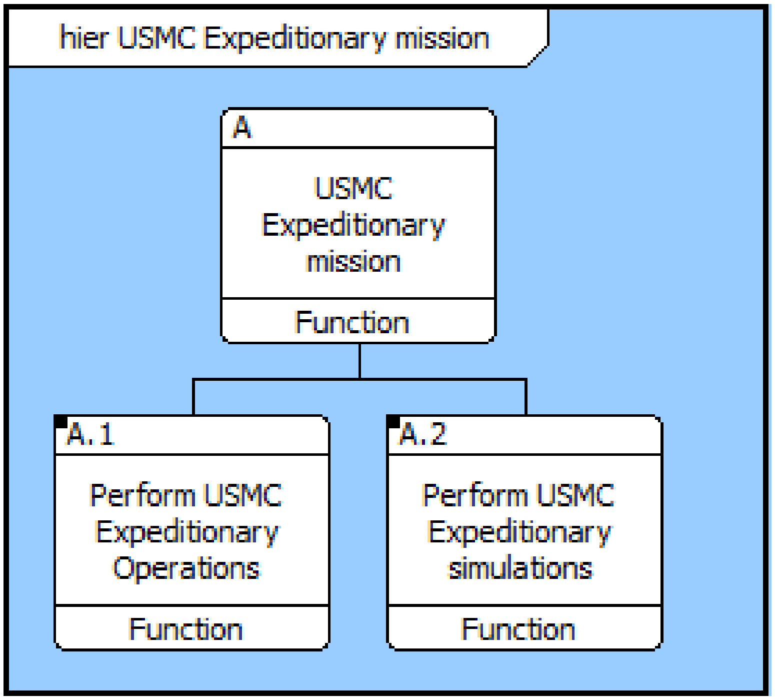


Figure 6. Top Level USMC Mission and M&S

III. SCENARIO DEVELOPMENT

Scenario development for an Amphibious Assault began by studying previous capstone project approaches to the seabasing mission outlined in the "Seabasing Annual Report for Program Objective Memorandum 2017." Within the report seabasing is described as "support[ing] five overlapping lines of operation: Force Closure, Arrival and Assembly, Employment, Sustainment, and Reconstitution," or "CAESR" for short (USMC 2015, 4). Previous capstone projects studied the Force Closure operations within an antiaccess/area denial (A2/AD) environment. This capstone project continues that work by studying the Employment operations within an asymmetric A2/AD environment. The mission selected for this capstone project was based on the scenario outlined in prior capstone reports.

The manner by which the seabase is configured as well as the personnel and equipment sent ashore are both dependent on the threats and tactics that will be faced by the USMC and USN forces during the Employment phase. The effects of modifying the DOTMLPF-P processes of Assembly and Employment must also take into consideration a scenario that represents the full mission, through the Sustainment and Reconstitution phases, of the Marine Corps. For this capstone project, it was assumed that the Assembly phase successfully and fully prepared the forces to execute the Employment phase and was not included as a part of the scenario.

The detailed Red and Blue Force scenarios for the seabase-to-shore effort are described in Section A, highlighting the concept of operations (CONOPS), overall scenario, and threat scenario. Section B details the sustainment operation on the shore that was studied as a part of this capstone project.

A. AMPHIBIOUS LANDING IN AN A2/AD SCENARIO

This scenario used for this project was derived and adapted as a follow on to the previously completed capstone project "Transportation Analysis Exploring Alternative Shipping of Marine expeditionary brigade Forces to seabase in Contingency Response Scenarios." The overall seabase CONOPS includes five distinct phases: Close, Assemble,

Employ, Sustain, and Reconstitute (CAESR). This scenario continues from the Close phase of the previous capstone project into the Employ phase, with the Assemble phase assumed to have been successfully completed to support the scenario outlined below. Within the Employ phase, the General Unloading condition, which is the portion of the phase where connectors are delivering personnel and equipment to shore continuously, was selected as the context for the ship-to-shore movement analyzed in this study. The General Unloading condition emphasizes speed and volume of throughput, which allows for the analysis of various combinations and loadouts of connectors. The selection of this condition allowed the analysis to be unconstrained by the strictly controlled movements of units and supplies ashore that define other portions of the maneuver, and largely dictate the timing, speed and order of the connector movements. It also provided a context for analysis where less modeling emphasis could be placed on threat and casualty implications, and greater focus placed on the employment of the surface connectors.

This capstone project focused only on Phase I of the provided Scenario, from seabase to the shore site, and the transportation of troops, platforms, supplies, and logistics support to the shore site. As requested by the Marine Corps E2O at the initial stakeholder meeting, an additional analysis of shore site electrical power generation was conducted to determine a potential solution to reduce the Marine Corps dependence on diesel power generation.

1. Tailored Concept of Operations

The scenario began with the occurrence of a crisis in the USPACOM AOR. The National Command Authority (NCA) determined the appropriate military response, and the Chairman, Joint Chiefs of Staff (CJCS) issued a warning order (WARNORD) to USPACOM with mission objectives (Bourgeois 2015). Marine Forces Pacific (MARFORPAC) established a seabase location and deployed a MEU sized MAGTF. The MAGTF maintains readiness by operating the command element (CE) from the seabase while coordinating daily drills as they prepare for a STOM. MARFORPAC planners modify existing operational plans (OPLANS) based on the availability and capability of

sea and air lift connectors; sea, ground, and air attack platforms; time to close from seabase and surrounding locations; and fuel consumption for the shore based supply.

The STOM is executed in two phases in accordance with a STOM notice. The full CE, ground combat element (GCE), and logistics combat element (LCE) are deployed to shore in accordance with Phase I of the STOM notice. The fourth MEU Component, the MAGTF aviation combat element (ACE), operates from the seabase to reduce the footprint of the MEU and preserve fuel usage. The second phase of the STOM notice forward deploys a portion of the GCE 135 NM north from the CE site to the FOM site. Phase II is beyond the scope of this study. The Phase I objectives of the STOM notice include the repositioning of the seabase 12–24 NM from the shore site landing zone (LZ) and the forward deployment of three of the four MEU elements from seabase-to-shore.

The MAGTF commences STOM planning immediately following receipt of the notice from MARFORPAC. Surface connectors are obligated and readied for equipment and personnel uploading. Air lift connectors are placed on ready standby to deliver the GCE equipment and personnel if the timeline to intervene is accelerated. Attack aircraft are placed on ready standby to provide CAS and CAP as needed. Small UAVs are used to provide aerial ISR and to detect and locate Red Force activity. If Red Force A2/AD activity increases during the STOM, aircraft are launched to provide aerial combat cover and to protect the force while the sea lift connectors are operating. Notably, the A2/AD tactics employed by the Red Force increase fuel consumption if aviation assets are required to protect or transport the Blue Forces. The aviation related fuel consumption, however, is not analyzed within the scope of this capstone project. Figure 7 shows the current location of the seabase, its projected closest location at 12 NM from the LZ, bidirectional sea lift connector lanes between the seabase and LZ, and the intended air and land GCE deployment route to the FOM site.

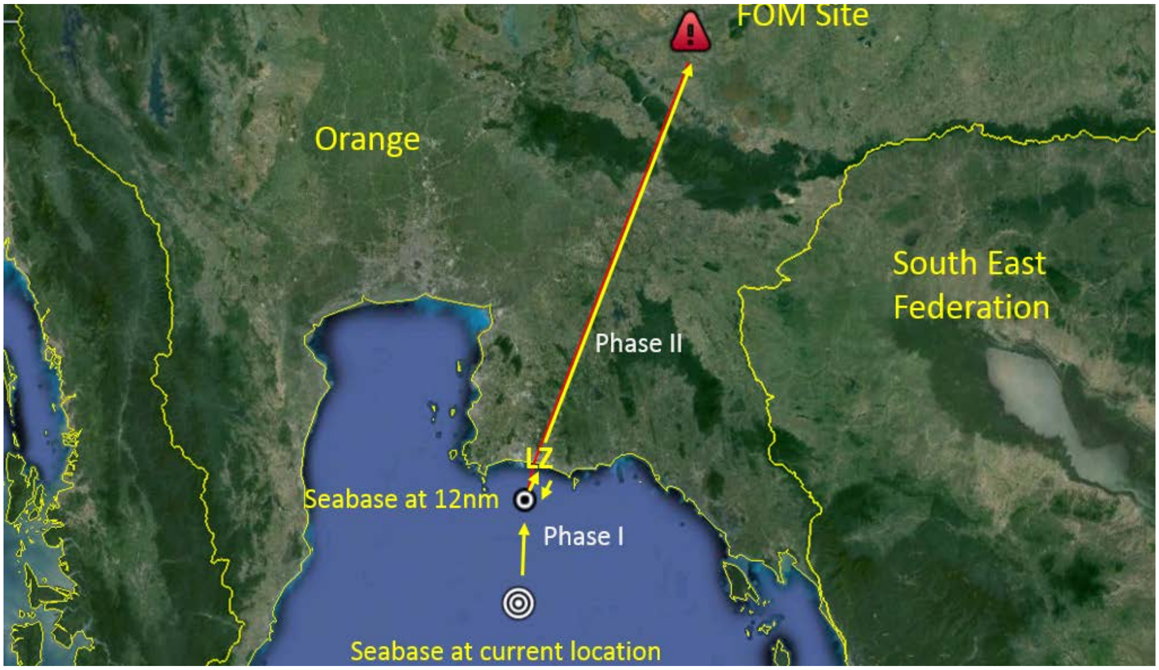


Figure 7. STOM CONOPs. Source: Google Earth (2016).

The first portion of the MEU to go ashore is the GCE, which establishes a secure perimeter three miles inland for the CE. The remaining CE relocates from the seabase to the secure perimeter on GCE notification. The MAGTF LZ, the secure perimeter for the CE, and the GCE movement to the FOM site are all within the nation of Orange. Figure 8 shows the OV-1 for the STOM that transfers the GCE, CE, and LCE to shore. The CE operating aboard the seabase controls and coordinates the transfer of equipment and personnel. The CE on the seabase continues to control and monitor transfer activities while the ground based CE personnel and equipment are detached, uploaded, and transferred to shore under the control of the CE operating on the seabase. Next, the LCE transfers to shore in support of the ground forces.

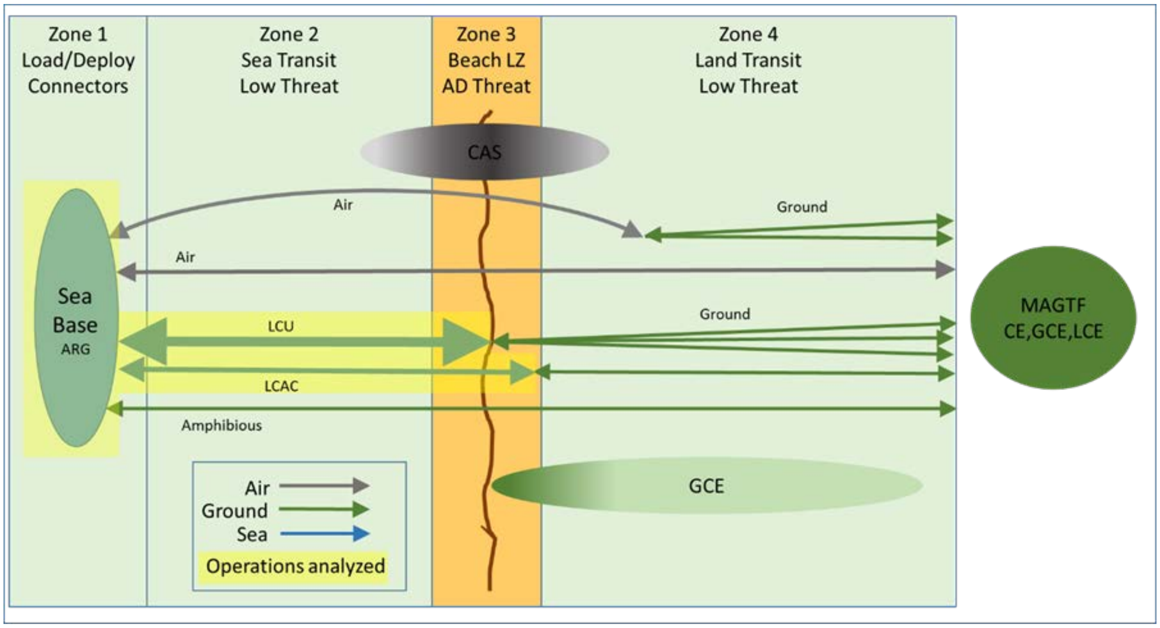


Figure 8. STOM OV-1

Once ashore, the deployed MEU is authorized the use of alternative and renewable energy systems to reduce dependency on fossil fuel consumption and the demand on fuel supply system infrastructure during the Sustainment phase. Fuel and supplies are delivered to the deployed MEU continuously during the Sustainment phase, enabling the execution of Phase II of the STOM. Sustainment is the costliest of the phases in terms of fuel usage for a MAGTF; it is also the longest of the phases. The sustainment continues until the CE's ashore and aboard the seabase initiate the Reconstitution phase of CAESR.

2. Detailed Scenario

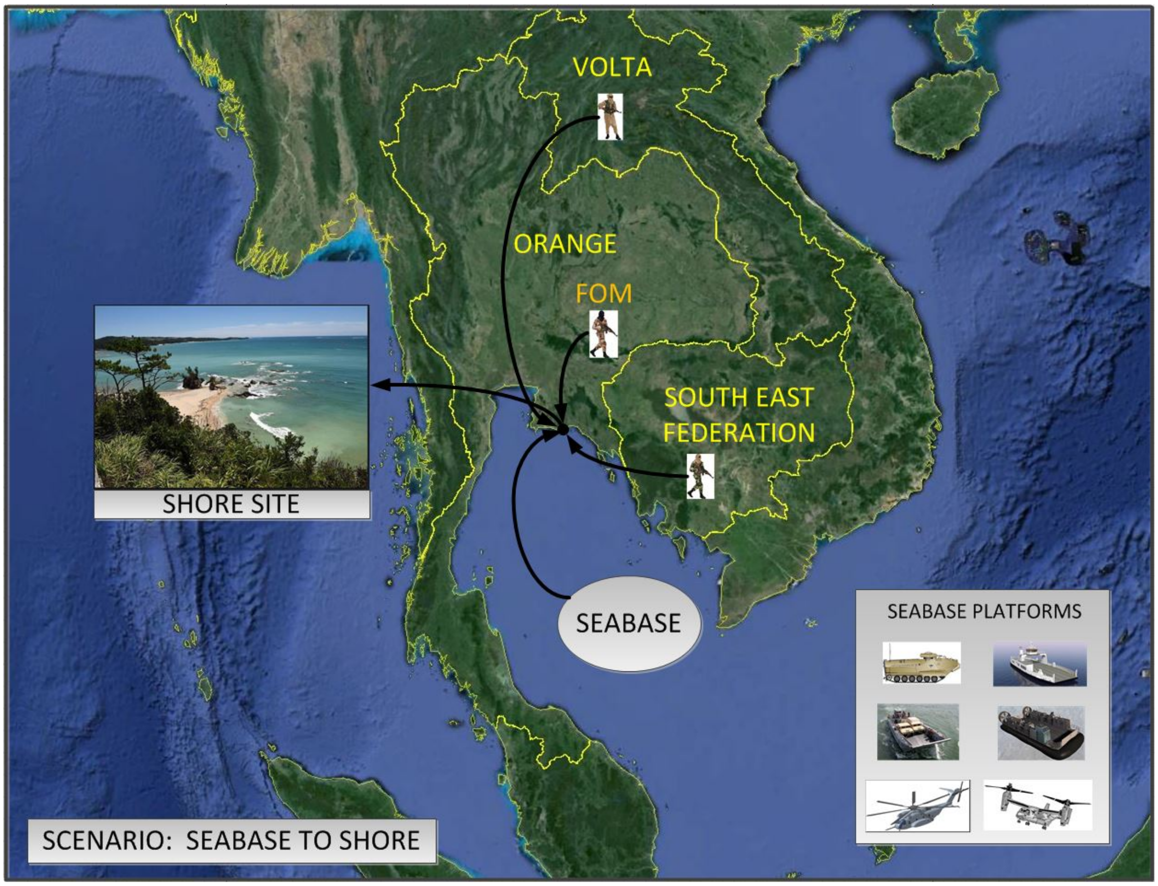
The nation of Orange, a U.S. ally, is a politically unstable country in the USPACOM AOR. A hostile terrorist organization, the Free Orange Movement (FOM), is seeking to overthrow the current Orange government. The FOM is an irregular force consisting of 250–1250 troops posing an asymmetric threat to the Orange government. The FOM is supported by the South East Federation (SEF), a neighboring country that is an enemy of the nation of Orange, and Volta, a country that has pledged support to the FOM should the U.S. (Blue Forces) intervene to protect the nation of Orange. It is

believed that the SEF and Volta forces could quickly orchestrate an invasion of Orange in support of the FOM in as little as 4–12 hours.

The Blue Forces have pledged support to the nation of Orange and are planning a quick-reaction, crisis-response mission to attack the FOM land site in an attempt to destroy FOM resistance and restore peace and prosperity to the nation of Orange. To do so, the Blue Forces have currently positioned a seabase off the coast of Southeast Asia as a staging point from which to launch this effort. The Blue Forces consist of one MEU comprised of approximately 2200 Marines and Sailors nominally embarked aboard several amphibious ships and will conduct this operation in two phases:

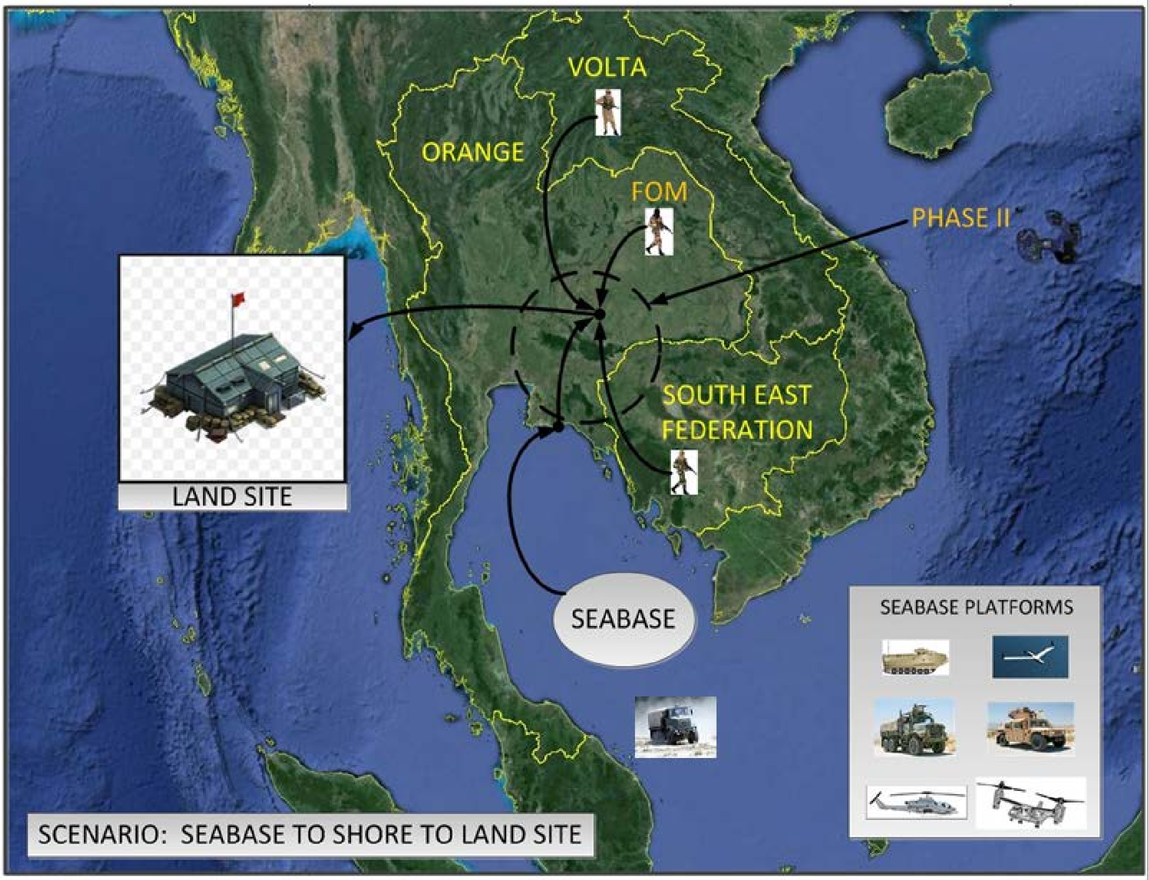
Phase I - From Seabase-to-Shore Site (Figure 9) (This Capstone Project)

Phase II - From Shore Site to FOM Land Site (Figure 10) (Future Capstone Project)



Photos from Mcclatchydc.com (2016), dreamstime.com (2016), modelairplanecolletors.com (2016), marinelink.com (2016), benefits.military.com (2016), turbosquid.com (2016), globalsecurity.org (2016), wetcanvas.com (2016).

Figure 9. Phase I – From the Seabase to the Shore Site. Source: Google Earth (2016).



Photos from 337.com (2016), dreamstime.com (2016), modelairplanecolletors.com (2016), uni-drones.wikia.com (2016), army-technology.com (2016), timeofsandisego.com (2016), handofmanos.deviantart.com (2016), wetcanvas.com (2016).

Figure 10. Phase II – From Shore Site to FOM Land Site. Source: Google Earth (2016).

The Blue Forces have selected a shore site for their mission and plan to transport troops, platforms, supplies, and logistics support to this location in support of the follow-on attack of the FOM land site, Phase II. The shore site was selected for its surroundings to support an MEU sized MAGTF CE, however all of the coastline should be considered at risk from the FOM A2/AD effort.

3. Threat Scenario

The Major Combat Operations threat scenario was adopted from the Expeditionary Energy, Water, and Waste (E2W2), Initial Capabilities Document (ICD).

In that Scenario, first MEB is in the Assault Echelon of a Joint Forcible Entry Operation against an adversary state threatening regional stability. While Orange is an ally state, this scenario was determined to be the most suitable based on intelligence pertaining to the motivations and threats of the neighboring hostile states. It is assumed that the situation in Orange will rapidly escalate to include adversary state actors. The scenario is modeled around a STOM landing against an enemy with the potential to employ hybrid warfare tactics aimed a denial of secure areas and main support routes (MSR).

The FOM is a well-organized, yet irregular, force that uses asymmetric tactics to make up for relatively smaller numbers. The enemy forces are expected to be a mixture of irregular infantry with small-arms fire (SAF) machine guns, irregular infantry with rocket propelled grenades (RPGs), and defensive measures that include improvised explosive devices (IEDs) scattered along the coastline. The potential for integrated A2/AD threat with the coast protected by RPG fire should be anticipated. As prescribed in Expeditionary Force 21, this threat necessitates a SSD of 12 NM or greater until the threat is mitigated. These guerrilla tactics were assumed to consist of small scale engagements with FOM forces firing several shots before dispersing to cover to prevent return shots being fired, or were dispatched by CAS. It is expected that as the Blue Forces attempt to secure a shore site location, the FOM will immediately request reinforcements from SEF and Volta nations. The SEF forces, since they are closer to the Orange coastline, could provide support in as few as four hours. The Volta forces, since they are farther away, require more time before they are on site to support FOM efforts against the Blue Forces. Both SEF and Volta forces use similar weapons such as RPGs and man-portable small-arms, generically SAF.

4. Seabase-to-Shore Operations – Functional Architecture

The capstone team decomposed the first function “Perform USMC Expeditionary Operations” into the discrete functions shown in Figure 11. The capstone team used these functions to establish the process flow for performing the operations; which, in-turn, were used to create the simulation for analysis. For this capstone project, only the first two elements were explored: “Transfer from seabase to shore” and “Provide shore site energy

logistics.” The function “Transfer from seabase to shore” describes the primary top-level function analyzed, and captures the sub-functions required to transfer the MEU from the seabase to the shore in order to complete the mission. Through the process of transfer, everything that is needed by the MEU is transported. The function also accounts for any threats encountered during transfer. The function “Provide shore site energy logistics” captures the fuel burn rate and energy demand of the MEU while operating ashore. The breakdown of this function provided an understanding of how renewable energy can be used to support the MEU. The functions not studied, shown in red in Figure 11, require more time to complete, and are identified as candidates for future study.

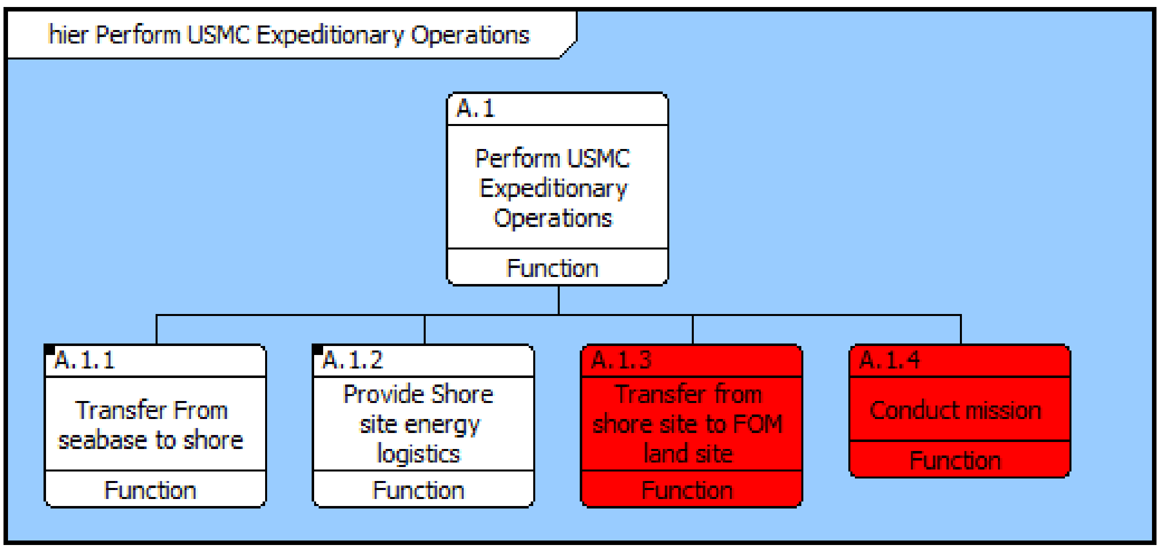


Figure 11. Hierarchical Function Structure of Perform USMC Expeditionary Operations

The function A.1.1 can be furthered decomposed into four sub-functions as shown in Figure 12. The function “transfer from seabase to shore” has many sub-functions that needed to be simulated to ensure the study is done correctly. Understanding that personnel and equipment needed to be transferred while countering A2/AD was required. Figure 12 shows these functions captured in a hierarchical method and are further broken down in the CORE models. These functions are needed to ensure that the MEU is fully equipped and protected for the mission.

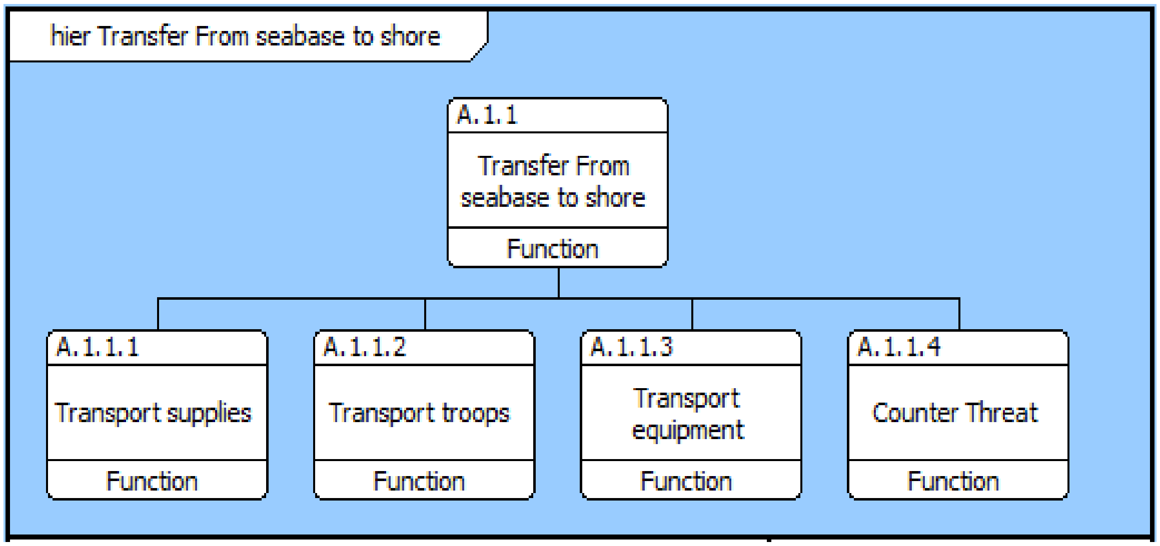


Figure 12. Breakdown of Function "Transfer from Seabase to Shore"

To understand how each function is related to another, an Enhanced Functional Flow Block Diagram (EFFBD) is used to display that relationship. Figure 13 shows one of the top-level functions "Perform USMC Expeditionary Operations" with the sub-functions relationships. As shown in Figure 13, "Transfer from Seabase to Shore," "Provide Shore Site Energy Logistics," "Transfer From Shore Site to FOM Land Site," and "Conduct Mission" are executed in sequential order. Understanding that these functions are not fully coupled allowed different simulation efforts to happen. These functions are conducted in phases in the operational environment which allowed the team to use different simulation tools without adversely affecting the outputs of the models. Since this capstone study only captured the first two sub-functions, the results can be used to continue the study of the other two functions. More detailed information can be found in Appendix A for relationships of sub-functions.

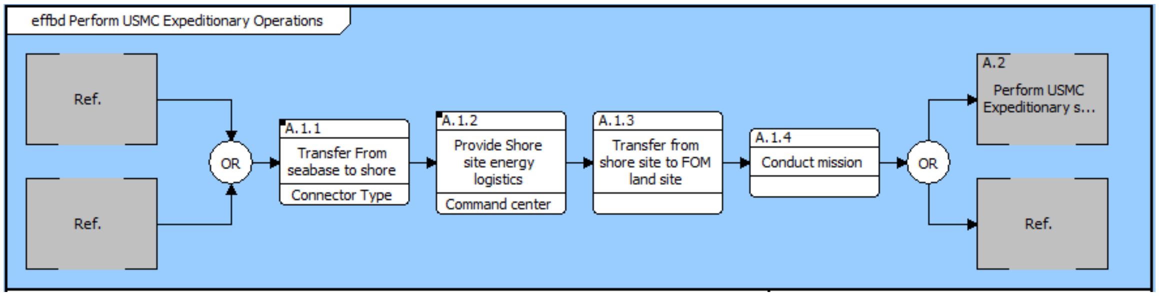


Figure 13. Functional Flow of Perform USMC Expeditionary Operations

B. SUSTAINMENT OPERATIONS (SHORE SITE)

During the Employment of troops in this capstone project's scenario, a Sustainment operation must begin to support the personnel and equipment that is landed ashore. This sustainment effort continues through Phase I and into the completion of Phase II where the MAGTF reaches its objective. As requested by the Marine Corps E2O at the initial stakeholder meeting, this capstone project, as a secondary objective, studied alternative and renewable energy sources to be used during the sustainment operations. The study determined whether solutions existed that could provide increased energy efficiency using alternative energy sources for shore site electrical power generation, while still maintaining operational effectiveness.

1. Alternative Energy Source Evaluation

This evaluation of alternative energy sources was completed using a systems engineering approach to assign qualitative and quantitative rankings to technical criteria for each energy source to obtain a defensible solution. The viable alternative energies were then simulated in the MAGTF Power and Energy Model (MPEM) to obtain power generation capabilities for a three-day operational scenario. These power totals were then further evaluated against USMC renewable energy goals to determine the number of alternative energy systems required to meet the renewable energy goals. For fiscal year 2016 the USMC Expeditionary Energy Strategy and Implementation Plan identified a 28% renewable energy goal (USMC n.d.-b, 22). MPEM equipment library entries were created for military-grade commercially-available systems based on the selected alternative energy sources and analyzed in MPEM. These library entries are available for

reuse as needed by the sponsor. The analysis of energy usage at the shore site provided an incremental burn rate based on the total number of troops, platforms, supplies, and logistics support that have been moved to shore, and the operations that are being carried out at the time. The capstone team assumed that this usage would increase alongside the quantity of personnel and equipment on shore, as it came online and began to be used. The energy usage totals utilized an existing MPEM library entry for an MEU. The first phase will be considered complete when everything has arrived at the shore site, and the remaining employment and sustainment phases will continue on at full burn on the shore site.

The USMC Expeditionary Energy Strategy and Implementation Plan indicates "yet we have also become increasingly dependent on fossil fuel" (USMC n.d.-b, 3). The Implementation Plan continues by discussing how the dependence "degrades our expeditionary capabilities and ultimately puts our Marines at risk" (3). Also, according to the plan and based on previously collected data, there is a typical fuel usage of eight gallons per Marine per day (GPMD) (USMC n.d.-b, 27). Extrapolating this data for an MEU, which is the smallest MAGTF unit at approximately 2200 troops, it is typical for tens of thousands of gallons of diesel fuel to be consumed in any given day during Sustainment operations depending on the mission being performed. The USMC "requires an expeditionary mindset geared toward increased efficiency and reduced consumption, which will make our forces lighter and faster" (3). The need for "innovative solutions" integrated into the USMC operations "to reduce energy demand in our platforms and systems, increase our self-sufficiency in our sustainment, and reduce our expeditionary foot print on the battlefield" will allow the USMC to achieve its goal to reduce its fossil fuel dependency (USMC n.d.-b, 3, 27).

This need for diesel to sustain operations requires a steady supply chain of fuel to and from the seabase. Augmenting the traditional means of power generation with alternate energies would provide the ability to ride through peak power demands and reduce bulk fuel operations. Additionally, fuel transport in a hostile region provides a vulnerability that is usually exploited by the threat. Increased efficiency has the potential to reduce the logistics effort for fuel by decreasing the logistics infrastructure, saving

time and manpower in fuel transport, reducing the susceptibility to the logistics supply chain, and supporting additional mission payloads by replacing the saved fuel cargo with other mission critical supplies. Sustainable energy at the shore site would provide a real benefit to Blue Forces and could significantly reduce or eliminate transit time for a number of operations.

This capstone project identified what alternative energies should be further pursued for additional evaluation, an operational exercise, or eventually for utilization in a Program of Record (POR). Currently the E2O POR's are based on solar energy that provides only a limited amount of power generation. This capstone project explored a significantly greater power demand that exceeded the capabilities of the POR solar and indicated the need to explore alternative energies. The team observed that the MPEM libraries were based on traditional power generation methods only and therefore needed the addition of alternative energy sources to be included in the model to appropriately simulate the best possible energy generation solution. Additionally, this capstone project identified military grade commercially available systems specific to a recommended form of alternative energy. The results of the analysis with these systems determined the number of systems required to meet USMC renewable energy goals, so that the sponsor can better understand the quantity of systems required to support a sustainment scenario as outlined in this report.

2. Shore Site Operations – Functional Architecture

The sustainment portion of the capstone project is shown in Figure 14, the function "Provide shore site energy logistics" involved determining the fuel demand, setting up command, and analyzing requested supply quantities. These functions established the logistics required of the MEU during sustainment and were used to analyze how much energy generated by renewable energy could offset the fuel burn rate of the MEU. The analysis of the fuel burn rate for the MEU focused primarily on the MEU MAGTF command element, with most MEU vehicles considered to be self-sustained. For this capstone project, the study focused on renewable energy sources for the MAGTF command element's energy needs. This capstone project explored the

feasibility of adding to or replacing the MAGTF command element's diesel generators with renewable energy sources to reduce the demand for fossil fuels at the shore site. The energy consumed during the assembly of the MAGTF command element is also included as a function for obtaining these logistic benchmarks. Most of the energy utilized setting up camp involves vehicles which use diesel engines. The supply requests helped to analyze how much supplies and/or fuel is requested for a period of time, this function helped the capstone team understand how many trips a connector needs to perform during sustainment operations.

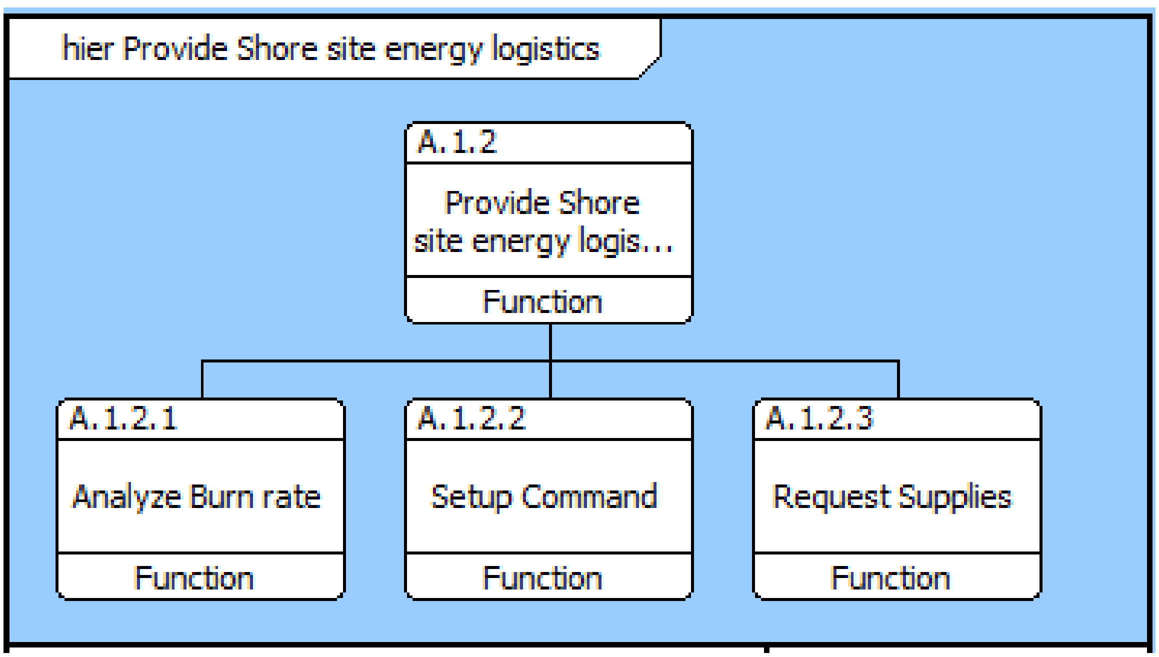


Figure 14. Breakdown of Function "Provide Short Site Energy Logistics"

In order to analyze the MEU performance in A.1.2, logistics metrics such as the fuel burn rate, the resource usage to setup command, and the frequency which supplies are requested at have to be collected. The energy analysis helped understand how renewable energy can be used in the field. Once the MEU is stationed at the shore site, the energy burn rate remains stable while the MEU is in standby mode. The resources needed at the shore site helped to provide a good estimation of the electricity demand of the MEU for analysis. The request for supplies was also a function that is performed by

the sustainment unit and captures how often refueling is needed. Further breakdown of these functions can be found in Appendix A, and were used to aid the analysis of the USMC operations.

C. SCENARIO DEVELOPMENT CONCLUSION

The scenario and the efforts of this capstone project were fictionalized and generalized with the intention of making the scenario, model, analysis, and results applicable to any situation that the USMC may face. Though not exhaustive, this scenario does include many of the major aspects of USMC missions, and joint operations. The scenario's assumptions were made only to limit the scope of the study and to allow for the capstone team to drawn useful and valid conclusions. The conclusions should then be used in an unburdened scenario to verify whether or not they are valid in additional instances. The scenario was divided into two parts for ease of analysis but could be evaluated in the future at a system of systems level by joining this capstone project's models with other previous and potential future models.

IV. MODELING, SIMULATION, AND ANALYSIS

The seabase-to-shore throughput analysis focused only on the employment of surface connectors. The energy efficiency of the connectors was dependent on many factors, which included the power plant of each platform, the amount of weight being transported, environmental conditions, and the asymmetric threats that could slow down or speed up the connectors. This will allow for a detailed exploration of the seabase interface, docking and loading operations, connector performance, the landing zone, and unloading operations. The seabase-to-shore throughput analysis also explored energy efficiency using traditional platforms, such as the landing craft, air cushion (LCAC); the Landing Catamaran (LCAT); and the Landing craft, utility (LCU); within the context of their tactical functions. The capstone team studied whether energy efficiency is increased through a change to Marine Corps tactics, a non-material solution, via the analysis of the traditional platforms

The capstone team also studied the materiel solution of changing the energy source used for USMC operations during the Sustainment phase. The team introduced and analyzed several alternative energy sources that could replace the traditional diesel generator systems, and whether these alternatives were feasible, viable, and available. Non-materiel solutions were not studied as the Sustainment phase portion of this capstone project was prioritized lower than the Employ phase portion.

A. SEABASE-TO-SHORE

The information provided in this section describes the M&S and analysis efforts for the seabase-to-shore STOM mission portion of the study. The capstone team built a model in ExtendSim that explored surface connector fuel consumption while executing a STOM mission with variable configurations of surface connectors and other input factors. The information in this section provides detail to facilitate the understanding of the modeling and simulation (M&S) and analysis efforts. This section details the functional architectures used for simulating the seabase-to-shore operation described in Chapter III, the physical architectures represented in the models, and how those architectures relate to

one another. This section also focuses on how the models were developed, verified, and validated. Lastly this section details the design of experiments, the results from the M&S activities, and the analysis done on those results.

1. Seabase-to-Shore Simulations Functional Architecture

The function "Perform USMC Expeditionary Simulations" emulates the function "Perform USMC Expeditionary Operations"; as such, the sub-functions are very similar. Figure 15, shows the decomposition of the function "Perform USMC Expeditionary Simulations." This decomposition helped the capstone team to create the simulation models. Each function had a different type of analyses conducted which is why they were separated. The function "perform mission" is not studied in this capstone project and is recommended for future capstone projects.

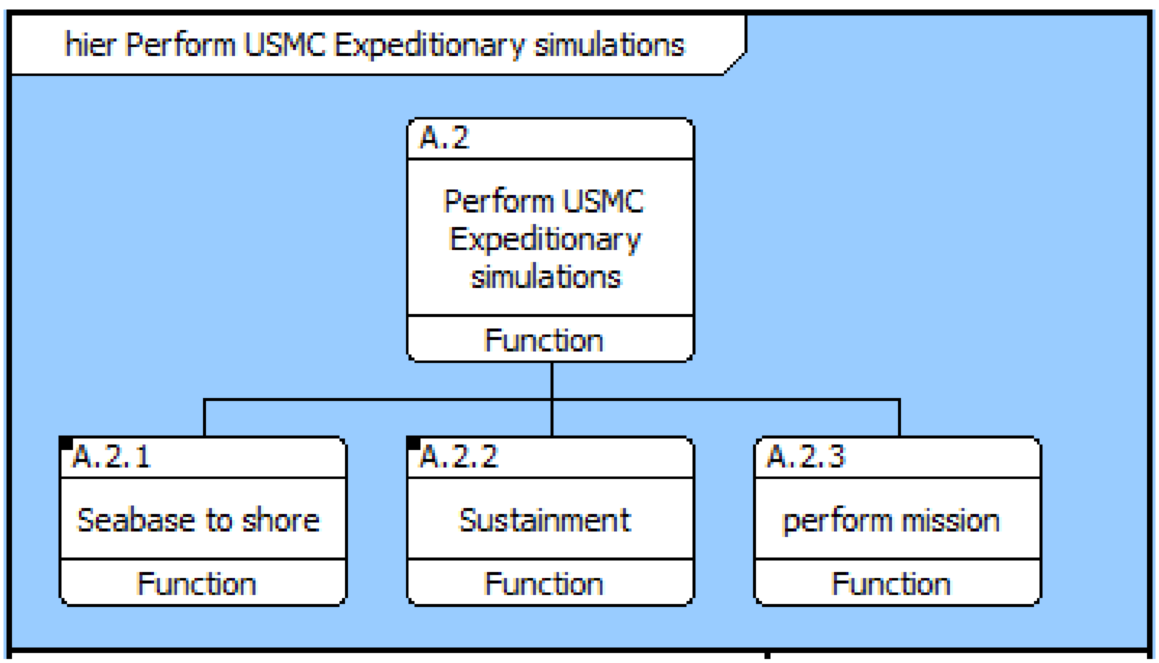


Figure 15. Breakdown of Function "Perform USMC Expeditionary Simulations"

The function "Seabase to Shore" under the simulation function is different from the "Perform USMC Expeditionary Operations" function because it is focused on model and simulation efforts only rather than the detailed sub-function efforts of the operations.

The sub-functions of A.2.1 shown in Figure 16, include the simulation tool that was used, Imagine That's ExtendSim, and all the appropriate steps to complete the function. These steps include getting the software initialized, running the software, obtaining results, and the final analysis of those results. Each of these sub-functions, however, has more detailed decompositions which can be found in Appendix B. These details include how the simulation effort was constructed in relation to the capstone project's scenario.

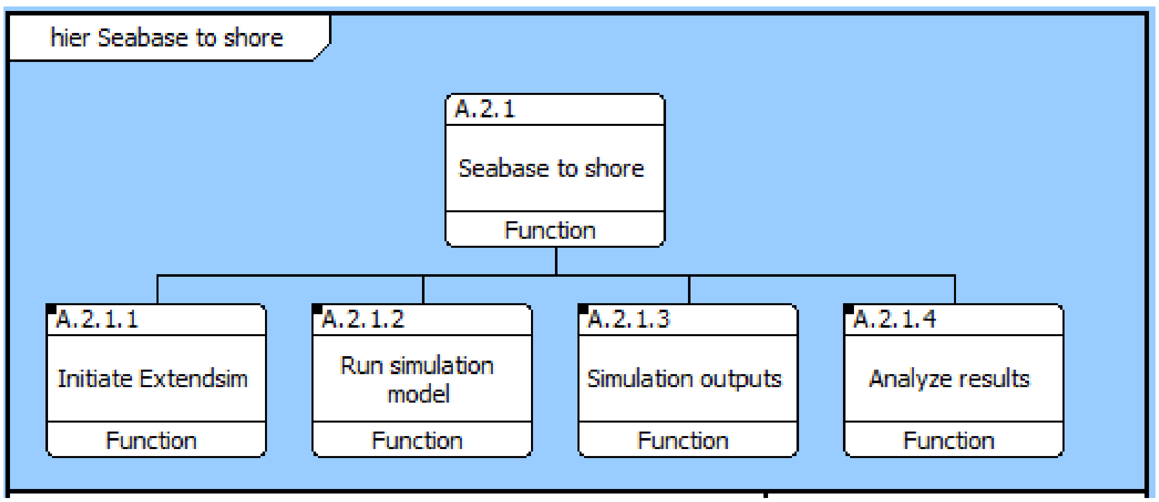


Figure 16. Breakdown of Function "Seabase to Shore"

With the mission decomposed, each element or function needed to be modeled in a simulation. The simulation model was decomposed into the sub-functions shown in Figure 17. These functions are related to the USMC operations and have the same sequential order. As previously mentioned, the main focus of the simulation is in A.2.1, "Seabase to Shore," and A.2.2, "Sustainment." The function "Perform Mission" captures both of the efforts not studied in the capstone project shown on the previous figure. By mimicking the Marine Corps Expeditionary operations, each simulation effort was conducted independently without needing the results from the other.

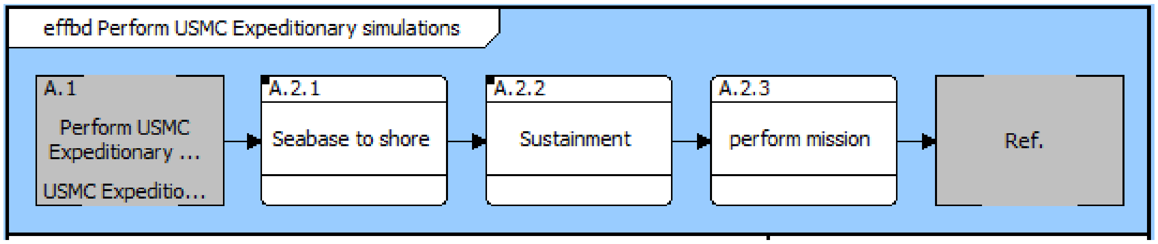


Figure 17. Function Flow of Perform USMC Expeditionary Simulations

The function A.2.1 was decomposed further to include actions needed to run the model properly. As shown in Figure 18, the overall steps on how to get the model running are shown. The first step to getting ExtendSim running is to initiate all the variables. This function allowed the programmer to set the parameters for the scenario into the model. After initiating the model, creating the scenario in the model for execution was needed. After the execution of the model, the results would need to be captured in a format that can then be analyzed. JMP Pro is used to analyze the results after the execution of the model. Each of these functions has sub-functions that can be found in Appendix A.

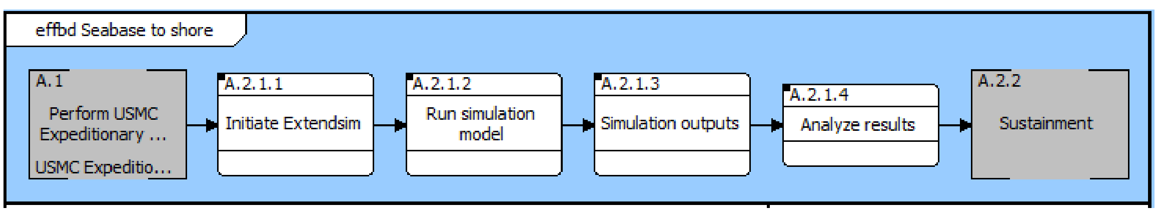


Figure 18. Seabase-to-Shore Functional Flow Block Diagram

2. Seabase-to-Shore Simulations Physical Architecture

The physical architecture for this capstone project included the Marine expeditionary unit (MEU), amphibious ready group (ARG), shore type, seashore connectors, supplies, and A2/AD threat. The team considered all components in the M&S effort performed during this capstone project. The components were mapped to the simulation using the Vitech CORE software which displayed the relation in the functional hierarchy diagram. As shown in Figure 19, the components were grouped into four

categories which were used to map the functions to the physical architecture. These relationships can be seen under each specific function in the functional hierarchy diagrams found in the functional to physical architecture mapping section, Chapter IV.A.3.

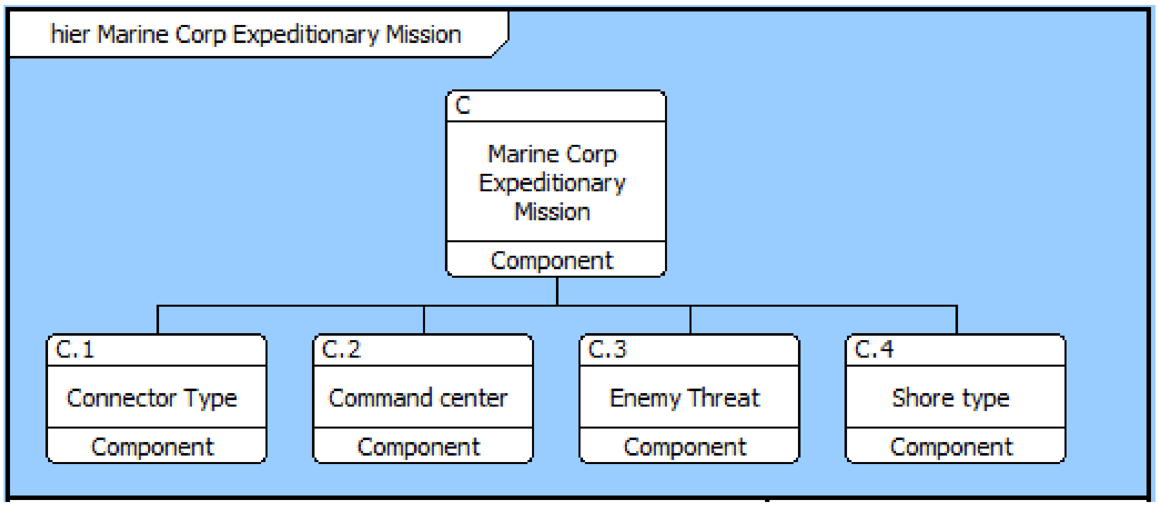


Figure 19. USMC Mission Physical Component Hierarchy

To support the USMC mission, a three-ship ARG was utilized to transport the MEU and supplies. The LCU, LCAC, and LCAT shore connectors were used in different configurations to study the performance of each. The specifications for each of these connectors is shown in Table 2. The ARG configured for this study consist of an LHD, an LPD, and an LSD. The configuration that was considered in this study is called a three-ship ARG and is commonly used in the USMC. The ARG utilized can load different quantities of surface connectors as shown in Table 2

Table 2. Connector Type Specifications

Connector	LCU	LCAC	LCAT
Lift (tons)	144	60	88
Deck Area (sqft.)	1850	1809	1367
Troops	400	180	300
Length (ft.)	135	88	98
Width (ft.)	30	47	42
Height (ft.)	18	24	20
Range (NM)	1200	200	500

Table 3. ARG Ship Specifications

Ship	LHD-1 Wasp	LPD-17 San Antonio	LSD-41 Whidbey Island
Troop accommodations **(#)**	2,104	799	504
Vehicle square (sqft.)	24,012	25,000	11,831
Cargo cube (cuft.)	145,000	35,000	8,970
JP-5 (gal)	484,000	215,000	53,000
Well Deck Dimensions			
L(ft.)	322	188	440
W(ft.)	50	50	50
H(ft.)	28	31	27
Number of Landing Craft per Type Accommodated in Well Deck			
# of LCU	2	1	3
# of LCAC	3	2	4
# of LCAT	3	1	4

For this capstone project, the arrangement of different connectors was studied to explore energy efficiency using the capabilities of each ship. Specifically, the capstone team evaluated 27 feasible combinations of connectors for a three-ship ARG. Further analysis was conducting by performing a DOE using JMP Pro. In addition to these combinations of connectors, there are three different A2/AD threats used for the capstone project. This allowed non-traditional threats to be part of the simulation to study how the model responded. These non-traditional threats included small-arms fire (SAF), improvised explosive devices (IEDs), and rocket propelled grenades (RPGs). These threats each had different effects on the overall model results.

3. Functional to Physical Architecture Mapping

The functional and physical architecture were mapped using Vitech CORE software. The software allowed direct traceability to requirements from functions and components needed for the system. CORE displays these relationships through the use of an Enhanced Functional Flow Block Diagram (EFFBD). This chapter will utilize these models for displaying the relationships between the components and functions.

From the overview of the function for the scenario, the main four functions are shown in Figure 20. The figure also shows the relationship to the components used for these functions under the function block. The function "Transfer from Seabase to Shore" utilizes the connector type components to perform these functions. Then, the function "Provide shore site energy logistic" is performed by the command element (CE) component. These relationships are shown for sub-functions in the architecture.

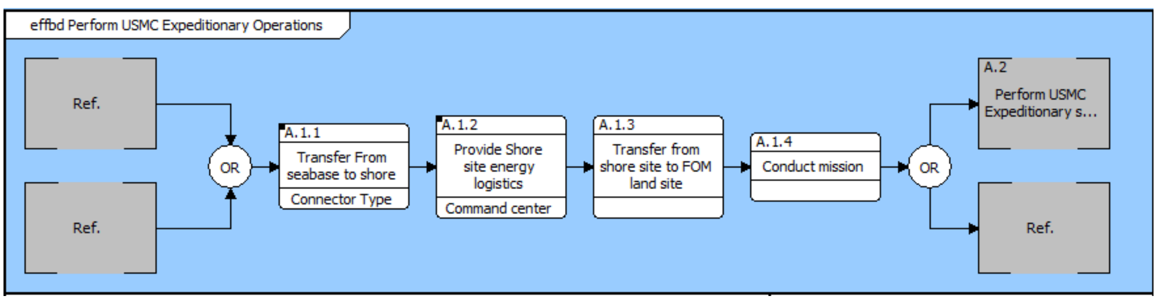


Figure 20. Functional Flow Block Diagram of the Perform USMC Expeditionary Operations Hierarchy

The sub-functions of "Transfer from Seabase to Shore" utilize the connector type components throughout each step. Figure 21 shows how transporting supplies, troops, and equipment are related to the connector type component. Even though there are additional interactions with other components, such as the ARG, these functions are primarily conducted by the connector type. Interaction to the ARG and the shore were assumed transparent to the model as stated in the assumptions section of this report.

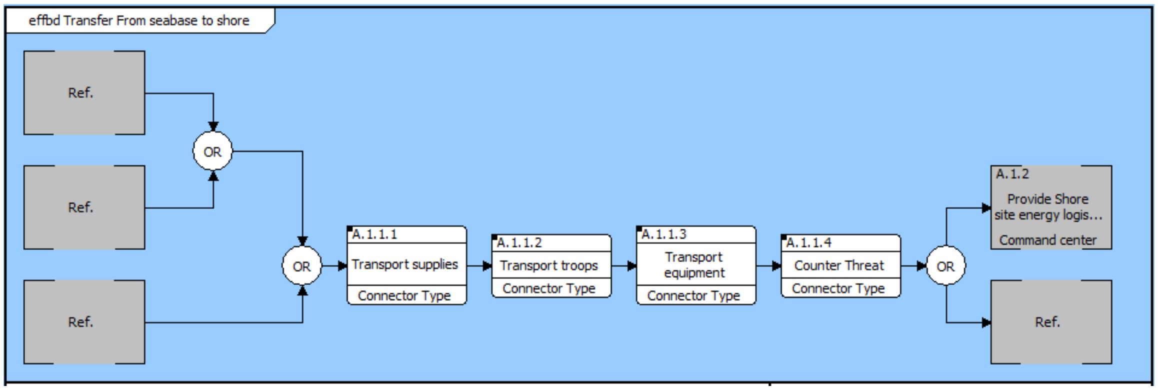


Figure 21. Seabase-to-Shore Function Relation to Physical Components

The sub-functions shown Figure 22, Figure 23, and Figure 24 are performed by the connector type. The reason these functions were shown was to demonstrate how other components are used in sub-functions. Figure 25 shows how the enemy component is performed in the counter threat function. To counter the threat, the enemy has to be present and the communication between the connector type and ARG exists. Most of the functions within the counter threat function are performed by the connector type except when the threat fires.

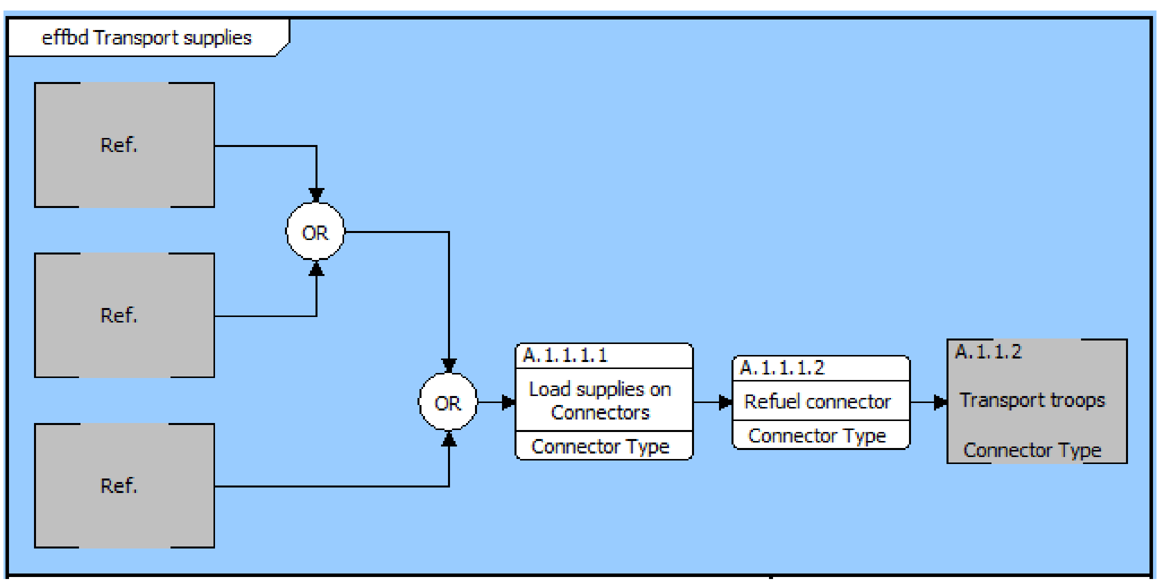


Figure 22. Transport Supply Function Relation to Physical Component

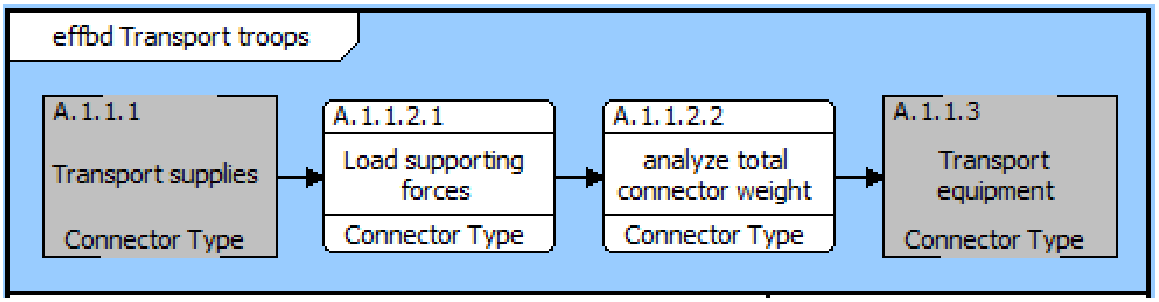


Figure 23. Transport Troop Function Relation to Physical Component

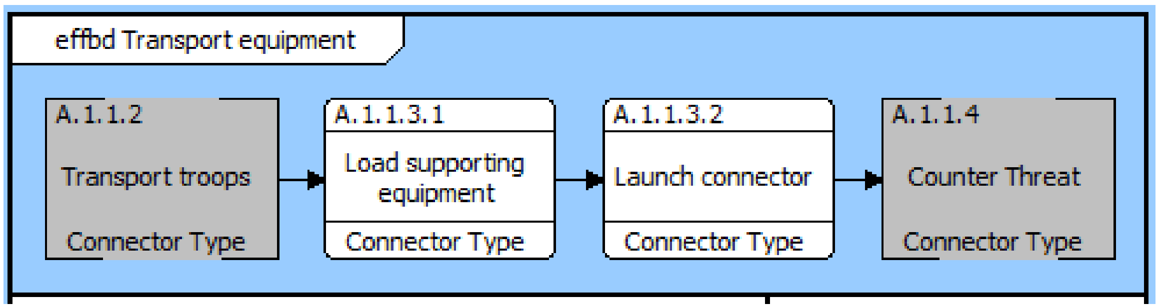


Figure 24. Transport Equipment Function Relation to Physical Component

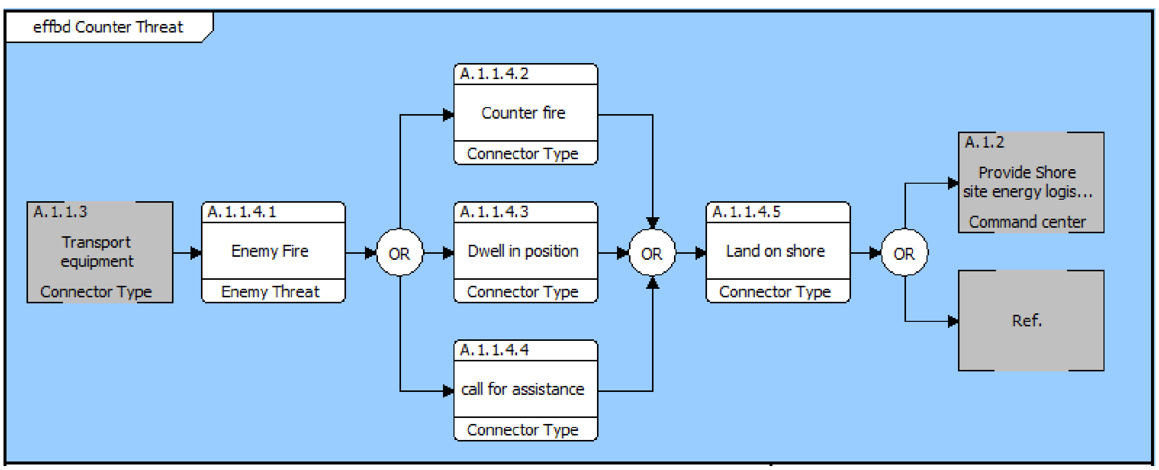


Figure 25. Counter Threat Function Relation to Physical Component

The second phase in the capstone project involved a shore site analysis of energy utilization. As shown in Figure 26, the functions are performed by the CE component. This capstone project used the Personnel and Equipment in a typical MEU to analyze the burn rate and reporting to the CE. The CE is the overall performer of each function.

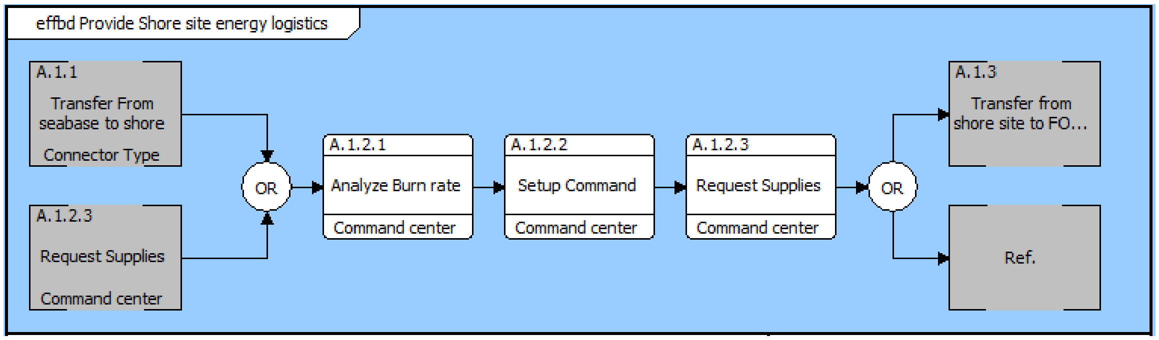


Figure 26. Sustainment Function Relation to Physical Component

The functions and component mapping enable traceability of each requirement to be shown. This ensures that each function specified is used and is aiming to complete the overall objective in the capstone project. By viewing the relationship between component and functions, it is possible to see any missed functions that were required. As stated, the components were properly mapped to each designated function and shown through the Vitech CORE EFFBD.

4. Model Development Approach and Process Steps

The team's first step was to define an approach for model development. This approach included the decomposition of the E2O problem statement, and set three primary expectations for the M&S effort: first to maintain the operational effectiveness of a Marine expeditionary brigade (or Unit) while reducing the energy footprint, second to include an A2/AD mission in the projected operating environment featuring a "non-traditional" environment with a "non-traditional" threat, and third to address deployment and support of an expeditionary force to stop the threat. These steps helped develop the model for this capstone project.

The approach began with determining the key performance parameters (KPPs) relevant to the problem statement. The mandatory KPPs from the JCIDS Manual dated 12 FEB 2015 were reviewed and three applicable KPPs were identified. These KPPs drive tasks in the MCTL which the team used to develop the MOEs and their supporting MOPs. The relevant KPPs were tailored to support the expectations listed in the E2O problem statement and are identified below:

1) Force Protection ensures that operational effectiveness is maintained by preventing the detection of personnel and systems and protecting them from hit, blast, flood, shock, and electronic attack if they are detected.

2) Survivability ensures that operational effectiveness is maintained by protecting systems and personnel using speed, maneuver, and armor while considering system redundancy and attack from traditional and chemical, biological, radiological, and nuclear sources.

3) Energy ensures that operational effectiveness is maintained by considering the fuel and electric power demand and conservation to ensure the operational reach of our force while protecting the energy infrastructure required to sustain mission operations. (JCIDS 2015)

MOEs and MOPs drove the trade space exploration within the model and are based on tasks from the MCTL such as MCT 1.3.1 Conduct Maneuver and MCT 1.3.1.1 Conduct ship-to-objective maneuver. Several MOPs were reviewed and tailored to support the expectations listed in the problem statement while meeting the capability requirements specified by the mandatory KPPs. The capstone team then traced these MOPs to the capstone project's tailored KPPs. The MCTL also provided additional references, such as the Marine Corps Warfighting Publications (MCWP) 3–1, 3–2, 3–11.4, and 3–25.10. These references were used to develop the conceptual model and methodologies for the STOM model, develop concept of operations, perform functional analysis, and construct a system functional architecture. Along with the MCTL and theses additional references, the capstone team developed requirements based on USMC/USN policies and identified model assumptions and constraints. The assumptions and constraints are documented in Chapter II.C and are not repeated here. Additional requirements were received during interactive meetings and follow-up requests for information sent to the E2O stakeholder POCs.

Next, the development approach dictated the creation of measures for the model and set threshold and objective values to drive variation in the simulation and explore the trade space. Table 13 and Table 14 in Appendix C show the model measures, the range of variation for each measure and the resulting MOE supported by that group of measures. Once complete, the amount of detail from problem statement decomposition was sufficient to begin the construction phase of model development and concurrently launch

scenario development and the DOE efforts. To aid in the creation of model input factors for the DOE, input factors were traced to the measures and were explored by the capstone project scenarios. Three database tables were created in the model to define surface connector performance characteristics, store input factors for scenario control and trade space exploration, and to define the mission module attributes. The database tables are named “Constants,” “Factors,” and “Load List,” respectively. All three of the input tables were configured prior to model execution and were read-only at runtime. Additional information is provided on these tables in subsequent paragraphs.

The capstone team created research questions that were used to drive the model outputs, and to incite significant conclusions for the study. Two database tables were created for the model, the “STOM” table stored the records that described the status of the STOM mission in detail, and the “Outputs” table captured a summary of the STOM results. These results were analyzed and used to answer the capstone team’s research questions. A trace was performed from the model input factors to the stakeholder requirements or, in lieu of requirements, to the MOE and its measures. Some of the requirements were given by the stakeholders but were not sufficient to complete the detailed analysis. Though these requirements were sufficient to scope the M&S efforts, influence database design, and influence model flow, the capstone team lacked sufficient guidance for the DOE and instead created the model measures listed in Table 13 and traced the model inputs to them.

Following the trace, the team created STOM scenarios that explored the throughput from seabase-to-shore. Two scenarios were created to explore this trade space and make recommendations within this report. The scenarios resulted in the technology insertion of the LCAT to explore the Alternative Landing Craft (ALC) connector solution. Twenty-seven (27) distinct scenarios bounded by a three-ship ARG were created to explore throughput improvement. The initial scenarios were studied to improve throughput using alternative energy sources and systems, and to improve throughput using DOTMLPF-P modifications. Interim Project Reviews (IPRs) were used by the team to engage the stakeholders and solicit guidance and feedback on all aspects of the team’s

efforts. The value added and clarity provided by this guidance and feedback had significant impact on the development the STOM model.

Four MOPs were primarily used in this study, the Mission Payload Transfer Time (MPTT) in minutes, the Total Fuel Used (TFU) in gallons, the Total Loiter Time (TLT) in minutes, and the Average Speed (AS) in knots. MPTT indicated the total simulation time to transfer the entire mission payload to shore. The mission payload was comprised of GCE, LCE and CE materials and personnel with a composite weight of 2,088.61 tons. The contents of each mission module and the weight and packing density was provided in a separate Excel workbook used to design and document our conceptual model. TFU recorded the total amount of fuel consumed by all surface connectors operating in support of the STOM mission. This value was calculated by launching all connectors with full fuel tanks, refueling them as they reached their bingo state (50% fuel remaining) and then a final refueling at the end of the STOM mission. All fuel transferred to the craft was logged in a global accumulator that was written into the Outputs table. The TLT of all surface connectors was calculated as a summation of A2/AD event durations and the time spent waiting/loitering for a well-deck to become available. During loiter the connectors transitioned to an idle power state to conserve fuel. A global accumulator was used to store and increment the loiter times for all craft and then written to the Outputs table. The AS of all connectors was calculated by adding the current speed of each connector to a global accumulator each time the connector information updated during the simulation. At the end of the STOM mission, the global accumulator was divided by MPTT and then by the number of connectors to calculate the average speed. A speed of zero was used while the connectors were in a loiter state.

5. Model Verification and Validation

The majority of model verification was achieved through testing and peer review of database values used by the model. A portion of the testing involved the use of a ModL function called UserError() that displays a dialog box with formatted results during runtime. This function was used for isolated testing of new ModL functions that were implemented in the primary code areas. Functional testing of isolated model segments

was used to simplify and reduce variables and to expedite results. The ExtendSim modeling suite contains testing infrastructure such as a programmable Plotter and database tables with output values that can be verified externally with spreadsheets and calculators. The capstone team verified the model in a series of peer reviews using Blackboard Collaborate to share the ExtendSim model, database tables, and ModL code.

Verification of function calls associated with probability distributions and random number generators were range checked to ensure the output values stayed within the minimum and maximum expected values. These areas of the code were verified using 300 STOM simulations where the STOM results were known and expected. The outputs were taken from the STOM table and analyzed in Excel to verify their range of values and report the impact of those ranges back to the team for discussion. Initially, the RPG A2/AD event was configured to launch with a probability of 10% but the team felt that the results did not realistically represent the concept of the guerilla warfare tactics discussed in Chapter III, and were therefore reduced to a more realistic 2%.

Validation of the model used several methods to prove accuracy and credibility. Mathematical and processing flow accuracy was tested and proven during model verification but did not address the accuracy of the range of the input values. Validation was performed iteratively throughout the model construction cycle so the model could be adjusted and improved as needed. Predictive validation was used in most cases; however, existing model comparisons, such as MPEM and the sea state table, were also used. Performance characteristics from face validity such as consults with a previous USNR/ LCAC Craftmaster and SMEs from the L-Class ships were also used. In addition to the three aforementioned validation methods, parameter variability was used by changing the model input values and determining the effects on model output. The model output responses were compared to the responses expected from a virtual system created from face validity (Law 2007, 257–264).

The STOM model obtained face validity and appears to be a reasonable imitation of a real-world STOM to the SMEs consulted. The credibility of the model increased also as buy-in from the SMEs involved in the consultations and reviews gained working knowledge of our STOM model. Graphical comparisons were made using the ExtendSim

Plotter and regression analysis where the current version of the model was compared to previous versions. Table 4 shows our E2O model data value assumptions and how the values were determined and their source of validation. The other data values loaded in the database tables have descriptions stating how their values were derived.

Table 4. E2O STOM Model Data Value Assumptions

Constant	Value	Description	Trace
Arrive	10 meters	Craft arrives at Destination when <= this distance	Reasonable assumption used in other models
RPGshot	0.02	2% probability from uniform pseudo-random number	Product of T&E and agreement with asymmetric warfare
RPGrng	1000 meters	rocket propelled grenade effective at this range	http://defense-update.com/products/r/rpg.htm
SAFrng	3000 meters	Small Arms Fire effective at this range	https://en.wikipedia.org/wiki/M2_Browning
IEDrng	300 meters	IED countermeasure distance	LCAC Craftmaster
JP5 FPR	300 GPM	LPD fueling system at 300 gallons of JP-5/minute	Naval Ship Technical Manual Chapter 542 Gasoline and Jp-5 Fuel Systems Rev 5
mNM	1852 meters	Meters to one nautical mile	https://en.wikipedia.org/wiki/Nautical_mile
Bingo	0.5	Refuel when level drops below this amount	LCAC Craftmaster
zT	30.866 meters	Z distance craft travel in meters at 1 kt for 1 minute	http://www.csgnetwork.com/csgtsd.html
FLR	1.2	Fast Loading Rate (20% increase)	Reasonable assumption from our conceptual model
WDC	3	Well Deck Count for three-ship ARG	Reasonable assumption from our conceptual model
cFBRoc	126 GPH	LCAC Fuel Burn Rate at Idle on cushion	Reasonable assumption from our conceptual model

6. Design of Experiments

This capstone team used the design of experiments (DOE) methodology as a comprehensive approach to define the combinations of input factors to be investigated in the model. The DOE was used to develop a design matrix from which simulation runs

were performed to obtain as much information as possible for the seabase-to-shore operational scenario. Selection of the DOE design type was critical in determining the combinations of factors required to properly evaluate the scenario without having an infeasible amount of simulation runs. To address this concern and to populate the DOE matrix, the team used a space filling design that minimized correlation between the input factors and maximized the coverage of the design space. These factors drove key design parameters and their responses were tied to the MOEs of the seabase-to-shore operational scenario. Table 5 shows the fourteen factors that this capstone project considered as variable simulation input parameters, and subsequently for the development of the DOE. In addition, Table 5 illustrates the M&S names used for each factor in the seabase-to-shore operational model, the specific meanings of each factor, the minimum/maximum values for each factor, and the relationship between each factor with the functional architecture of the seabase-to-shore operational model.

Table 5. Factors Considered in the DOE

Factor	M&S Name	Nomenclature	Minimum	-	Maximum	Relationship With Functional Architecture
LCAC Number	LCAC #	Number of LCACs for STOM	0	-	9	Function A.2.1 (Seabase to Shore)
LCAC Time Loading	LCAC TI	LCAC Load Time	Baseline	-	Baseline* 1.2	Function A.2.1 (Seabase to Shore)
LCAC Percent Load	LCAC %L	Percent LCAT Payload	50%	-	100%	Function A.2.1 (Seabase to Shore)
LCU Number	LCU #	Number of LCUs for STOM	0	-	6	Function A.2.1 (Seabase to Shore)
LCU Time Loading	LCU TI	LCU Load Time	Baseline	-	Baseline* 1.2	Function A.2.1 (Seabase to Shore)
LCU Percent Load	LCU %L	Percent LCU Payload	50%	-	100%	Function A.2.1 (Seabase to Shore)
LCAT Number	LCAT #	Number of LCATs for STOM	0	-	8	Function A.2.1 (Seabase to Shore)
LCAT Time Loading	LCAT TI	LCAT Load Time	Baseline	-	Baseline* 1.2	Function A.2.1 (Seabase to Shore)
LCAT Percent Load	LCAT %L	Percent LCAT Payload	50%	-	100%	Function A.2.1 (Seabase to Shore)
Seabase Standoff Distance	SSD	Distance to Beach (NM)	12	18	24	Function A.2.1 (Seabase to Shore)
Sea State	SS	Sea State Condition	1	-	3	Function A.2.1 (Seabase to Shore)
RPG	RPG	RPG Threat (0 no threat, 1 threat)	0 (0%)	-	1 (100%)	Function A.2.1 (Seabase to Shore)
IED	IED	IED Threat (0 no threat, 1 threat)	0 (0%)	-	1 (100%, 10%)	Function A.2.1 (Seabase to Shore)
SAF	SAF	SAF Threat (0 no threat, 1 threat)	0 (0%)	-	1 (100%)	Function A.2.1 (Seabase to Shore)

The capstone team did not explore all possible combinations of LCACs, LCUs, and LCATs because these additional combinations did not adhere to the definition of an ARG used in this study. Specifically, this capstone project considered a three-ship ARG for the seabase-to-shore operational scenario which has space and weight constraints that limit the number of each connector the ARG can hold, as well as the possible combinations of connectors that the ARG can support. The capstone team developed 27 realistic combinations for the number of LCACs, LCUs, and LCATs supported by the three-ship ARG. A 65 run Nearly Orthogonal Latin Hypercubes (NOLH) design was created for the remaining eleven factors to fill in the design space as uniformly as possible. Specifically, the capstone team used a NOLH design spreadsheet from the SEED (Simulation Experiments & Efficient Designs) Center for Data Farming, a Naval Postgraduate School website. This design facilitated the process for large-scale simulation experiments.

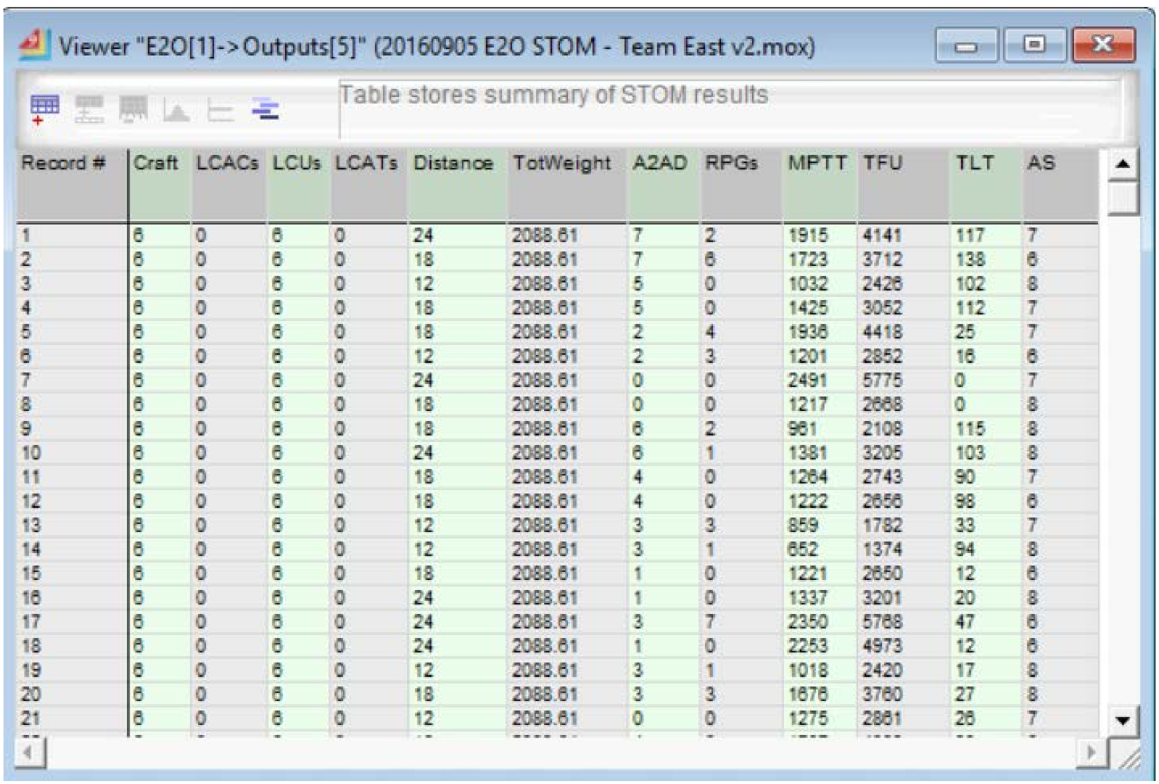
This capstone project used the NOLH designs spreadsheet as an efficient way to generate a design that reduce the correlation for the LCAC time loading, LCAC percent load, LCU time loading, LCU percent load, LCAT time loading, LCAT percent load, seabase standoff distance, sea state, small-arms fire (SAF) threat, IED threat, and rocket propelled grenades (RPG) threat to almost zero. Specifically, the NOLH designs spreadsheet ran an algorithm that essentially drives the correlation between these eleven factors to approximately zero, while ensuring maximum coverage of the design space. This particular step was critical for the DOE because if these eleven factors were highly correlated, then it would be extremely difficult for the capstone team to determine the effects of each factor during the regression analysis. The team investigated the NOLH design of these eleven factors for each of the 27 possible combinations of the number of LCACs, LCUs, and LCATs. Further discussion of the DOE approach can be found in Appendix D.

7. Model and Simulation Results

The model development, testing, and verification completed on schedule but the model had a runtime issue that had to be adjusted for the final 52,650 simulation runs.

The model could only complete about 800 simulation runs before the ExtendSim application ran out of memory and ceased running due to the excessive size of the STOM database table. The STOM table was bypassed in the model for the final simulations runs and completed the 52,650 STOM simulations in just over nine hours of runtime. The Outputs database table was verified for completion and spot checked for reasonable results and transferred into an Excel worksheet for follow-on analysis.

The new version of the STOM model was named E2O STOM v2 and was archived along with the original version. These models are available per request from the NPS advisors if a follow-on capstone team intends to build upon our baseline study version. A screen shot of our Outputs table is shown in Figure 27. Not all of the database fields shown were used for the follow-on analysis.



Record #	Craft	LCACs	LCUs	LCATs	Distance	TotWeight	A2AD	RPGs	MPTT	TFU	TLT	AS
1	6	0	6	0	24	2088.61	7	2	1915	4141	117	7
2	6	0	6	0	18	2088.61	7	6	1723	3712	138	6
3	6	0	6	0	12	2088.61	5	0	1032	2426	102	8
4	6	0	6	0	18	2088.61	5	0	1425	3052	112	7
5	6	0	6	0	18	2088.61	2	4	1936	4418	25	7
6	6	0	6	0	12	2088.61	2	3	1201	2852	16	6
7	6	0	6	0	24	2088.61	0	0	2491	5775	0	7
8	6	0	6	0	18	2088.61	0	0	1217	2668	0	8
9	6	0	6	0	18	2088.61	6	2	961	2108	115	8
10	6	0	6	0	24	2088.61	6	1	1381	3205	103	8
11	6	0	6	0	18	2088.61	4	0	1264	2743	90	7
12	6	0	6	0	18	2088.61	4	0	1222	2656	98	6
13	6	0	6	0	12	2088.61	3	3	859	1782	33	7
14	6	0	6	0	12	2088.61	3	1	652	1374	94	8
15	6	0	6	0	18	2088.61	1	0	1221	2650	12	6
16	6	0	6	0	24	2088.61	1	0	1337	3201	20	8
17	6	0	6	0	24	2088.61	3	7	2350	5768	47	6
18	6	0	6	0	24	2088.61	1	0	2253	4973	12	6
19	6	0	6	0	12	2088.61	3	1	1018	2420	17	8
20	6	0	6	0	18	2088.61	3	3	1676	3760	27	8
21	6	0	6	0	12	2088.61	0	0	1275	2861	26	7

Figure 27. E2O STOM Model Outputs Table (Example)

8. Statistical Analysis

The statistical analysis of this capstone project was conducted to determine the combinations of connectors from the 27 realistic scenarios that could comprise a three-ship ARG, and that provided the best performance in terms of throughput and energy efficiency. This was accomplished by completing a statistical analysis for all fourteen factors and four responses for all 52,650 simulation runs. In order to do this, metamodels were developed to provide estimated results for each of the four responses, and distributions of response data were created to identify limits with which to evaluate the scenario set. Analysis of the M&S response data was conducted utilizing these models against the limits in a number of graphs, matrices, and plots. These artifacts identified significance and insight into the solution space. Some of the graphs provided real time analysis through manipulation of the factors to determine the trade space, which was made possible by using predicted results. This trade space visualization provided the means to evaluate combinations of factors against the responses and present the results in such a way that conclusions could easily be drawn.

Development of the metamodels was an iterative process with multiple models being constructed and evaluated to determine the best model fit. Initially, the models were fit using different linear regressions and did not include any second order interaction terms using the 14 input factors. Analysis of the four responses identified curvature in the regression data which indicated the need for second order terms. A standard least squares fit was then run using second order interaction terms, and resulted in the generation of 87 interaction terms. These terms provided an excellent fit, but greatly complicated the analysis and made it difficult to gain insights and draw conclusions. In order to reduce the number of terms used in the metamodel, a stepwise regression was used to sequentially evaluate the input factor combinations. This regression produced a prediction formula with similar performance to the metamodel using the second order interaction terms. This evaluation was able to be viewed real time, with JMP Pro completing the regression by taking terms in-and-out and recalculating previous terms each time a new term is added. For this regression, the minimum Bayesian

Information Criterion (BIC) was used to determine which model type is used to stop the selection process.

The end result of the stepwise regression was a list of different models with their associated R-squared values. The list provided model selections with R-squared values that encompassed a range from low to high, with the highest values around 96%. The capstone team utilized the logic that any model with an R-squared value over 90% was explained sufficient variation that any additional terms provided little value, and was therefore chosen for each of the response variables. The difference between these new regression models and the ones previously created was that they had far fewer terms, making them far easier to interpret and explain. Once a new model was selected, a standard least squares regression was run with the limited subset of factors. This new regression explained the same amount of variability in the model when compared with the model created using second order interactions with approximately 70–80 fewer terms. The stepwise process was repeated for all four responses and resulted in four prediction formulas that were used for all further analysis. The statistical analysis regression plots shown in Appendix E, consist of the actual by predicted, summary of fit, analysis of variance (ANOVA), and sorted parameter estimates plots. These plots provided justification that all model fits were appropriate for further analysis.

One of the challenges the capstone team had with the regression was defining the type of variables used. For instance, many of the variables were discrete that should have been characterized by integers. This is most easily seen for factors such as connector type, the environmental constraints, and A2/AD effects. The difficulty was that the regression was a better fit when continuous variables were used, so the model was fit with continuous variables. This results in the reader having to interpret correctly the statistical data, expecting a step function, but appropriately deducing that continuous variables result in continuous curves.

After the team prepared the prediction formulas for the analysis, the team identified the response data limits for evaluation. The challenge was to select limits that met the needs of operational effectiveness, while also meeting E2O goals for energy efficiency. Response surface distributions were created for both the actual and predicted

results and are shown in Appendix F. Since the models each performed well with respect to the regression diagnostics, the distribution numbers were essentially the same. For this reason, the predicted distribution was utilized to develop the limits for use with the prediction formulas. The distributions provided a statistical summary of the data showing the distribution in terms of a percentage, with a lower quartile at 25% and an upper quartile at 75%. The capstone team decided these quartiles would best frame 50% of the data around the mean, in turn, showing a compromise between operational effectiveness and energy efficiency. Table 6 shows the response surface limits selected from these distributions. These limits were used to frame the solution space in the prediction profiler and contour plots.

Table 6. Response Surface Limits

Response Surface Limits Based On Response Surface Distributions							
Response	**Response Nomenclature**	**Response Goal**	**25% Quartile**	**Median**	**75% Quartile**	**Lower Limit**	**Upper Limit**
MPTT	Mission Payload Transfer Time	Minimize	598	780	975		975
TFU	Total Fuel Used	Minimize	18642	28420	40785		40785
TLT	Total Loiter Time	Minimize	72	133	191		191
AS	Average Speed	Minimize	12	15	18	12	

The next step in the statistical analysis was to identify which factors were significant in terms of contributing to the model variability. For this effort, normal, pareto, and sorted parameter estimate plots were reviewed for all four responses. While all of these plots are similar, the capstone team ultimately decided on using the sorted parameter estimates plots because they showed both the significance and the positive or negative influence of that factor. This helped the capstone team understand the impact that factor had on the particular response.

Substantial correlation was also noticed on some second order interaction terms as the significance was being evaluated. One such example was the product of the independent variables LCAC number and the LCU loading percent. The capstone team noted that when interactions like this are observed in the sorted parameter estimates table,

these terms related to high correlations between the connectors and the dependent nature of these variables. This dependence was due to the 27 realistic ARG scenarios limit used in this study. These second order interaction terms are the result of the statistical analysis software misinterpreting these highly correlated interactions.

This capstone project also selected four responses to explore in support of the seabase-to-shore MOE for throughput and energy efficiency. The first two responses MPTT and TFU, were considered the primary responses that were explored as they are directly related to this MOE. The second two responses, TLT and AS, were considered secondary responses as they were in support of providing a better understanding to the outcomes received for MPTT and TFU. The flow of the analysis typically followed the use of MPTT and TFU for the initial evaluation, with TLT and AS being evaluated in subsequent plots. It should also be noted that AS is the average speed of all the connectors being utilized in a given scenario. Since the capstone project only used idle and maximum speeds in the simulation, AS was calculated as the total speed for a given scenario by taking the total distance for all connectors and dividing by the MPTT.

The sorted parameter estimates plots are located in Appendix D as part of the regression plots and model fit parameters. The sorted parameter estimates plots for both MPTT and TFU identified significance for the following factors: seabase standoff distance (SSD), sea state (SS), the number of LCACs, the number of LCATs, the number of LCUs, and the percent loading for the LCAC. While the second order terms were not as statistically significant as the first order, there were some that merited further investigation including the number of LCACs multiplied by the LCAC percent loading and the number of LCATs multiplied by the LCAT percent loading. The second order analysis was conducted in the interaction profiler plot, showing the contribution these second order terms had on the output responses. The LCAC percent loading was further explored with the prediction profiler, which allowed the capstone team to see the tradeoff between the responses and the difficulties in selecting a robust value when there are conflicting performance goals. Additionally, the significance of each connector type was a good sign that the capstone team would be able to identify the best combination of connectors to meet the throughput and energy efficiency of the operational scenario.

It was also important for the capstone team to identify input factors that were not significant in the sorted parameter estimates plots, so that conclusions could be drawn on these parameters indicating why they were not further explored. The stepwise regression conducted for each of the responses reduced the number of terms for each of the metamodels. The capstone team noticed the effects of increasing the loading time for all three connector types were not included in all predicted formulas. This identified that increasing the loading time by 20% had little to no effect on the responses. The A2/AD effects on the response outputs MPTT, TFU, and AS were similarly insignificant.

As the capstone team progressed through the analysis, it was important to verify and validate the response data for continuity and agreement with design parameters. This was completed for the sorted parameter estimates, prediction profiler, and contour plots. For example, it was clear that a model based on the fuel efficiency of its connectors would identify significance with the SSD. Additionally, the A2/AD effects were based on the operational scenario being under general loading conditions, which dictate that the A2/AD effects are sporadic in nature since the landing zone has already been cleared of enemy forces.

The next step of the statistical analysis utilized the prediction profiler to analyze the effect of each factor across each of the four responses. The factors with the largest slope had the most substantial impact on a given response. The prediction profiler plot is shown in Appendix G. Since the number of metamodel terms was reduced during the stepwise model fit, the profiler only displayed the factors used in the prediction formulas. This greatly reduced the number of factors being evaluated, making the analysis much simpler than if there were a larger number of terms. The number of connectors, SSD, SS, and LCAC percent loading had the steepest slope for each of the four responses, suggesting that those variables have the most substantial impact across the full range of MOEs.

The prediction profiler also contains a function that allowed the capstone team to maximize desirability. This function returned the optimized value of each factor for a provided set of response desirability. The limits for the scenario obtained from the response surface distributions were input into the profiler and displayed in the desirability

column. These limits worked to minimize MPTT, TFU, and TLT, while maximizing AS. The maximize desirability function worked to optimize the input factors to the selected desirability inputs and displayed the optimized values for each factor in the desirability row. The four responses provide a paradox as each are competing against each other to determine an optimized value for each factor. These optimized values were then evaluated to determine which factors to hold constant, and which to further explore in the contour plots. The percent loading parameters were evaluated to determine what loading condition best met operational effectiveness since the focus of the capstone was to determine the best combination of connectors to complete the operational scenario. The response surface had very little slope for the LCU and LCAT percent loading, which identified that 100% loading provided the most throughput. The prediction profiler determined the optimized value for the LCAC percent loading was 86% due to the propensity of increased loitering time in conjunction with the increased loading percentage of the LCAC. A side effect of the increased loitering time was that the AS of the scenario was also decreased. The capstone team decided to utilize a LCAC percent loading of 100%, since TLT and AS were secondary responses and the MPTT and TFU returned the best values for 100% loading.

Also of interest in the prediction profiler was the combination of connectors returned when desirability was maximized. The prediction profiler identified that five LCAC, zero LCU, and zero LCAT provided the best combination of connectors for the response surface limits. This again, was a result of all responses having equal weighting and is not a realizable solution based on the three-ship ARG. This combination provided the insight that there is a point of diminishing returns where additional connectors do not provide a benefit in a scenario. For instance, the LCAC connector shows increased TLT as the number of LCACs is increased. In order to maximize desirability, a quantity of five LCACs was found to be the optimal number for all output responses. Recall that this desirability was for the shortest seabase standoff distance and lowest sea state because this is where desirability would be maximized. This capstone project worked to obtain the best combination of connectors for all values of SSD and SS, so the constant factor

values determined from the prediction profiler were subsequently entered into the contour profiler to determine the best combinations of connectors for each scenario.

The contour plot took the constant factor values determined in the prediction profiler and the limits from the response surface distribution and explored the best combination of connectors for each of the 27 scenarios. The connectors were evaluated first for throughput and fuel efficiency by viewing whether the combination of connectors was feasible under the given scenario conditions. The cross-hairs for the X and Y factors were set at the specific number of each connector type. Since the plot is only two-dimensional, only two factors could be displayed at any given time, but the contour plot does provide the solution space for all the factor inputs. Next the distribution limits were provided for both the MPTT and TFU responses. If the cross-hairs fell in the solution space, then that combination of connectors met mission effectiveness for that SSD and SS combination. The SSD and SS were increased one increment at a time to determine the maximum value for the SSD and SS that each scenario could be completed with. The contour plots for this condition were titled "Solution Space Contour Plot" and were the first plots provided for any given scenario. As an example, Figure 28 shows the solution space contour plot for scenario number six. If a scenario failed to have a solution space for a combination of SSD and SS, the limiting response was identified. The remainder of the solution space contour plots can be found in Appendix D.

Scenario #6		
LCU	LCAC	LCAT
2	2	4

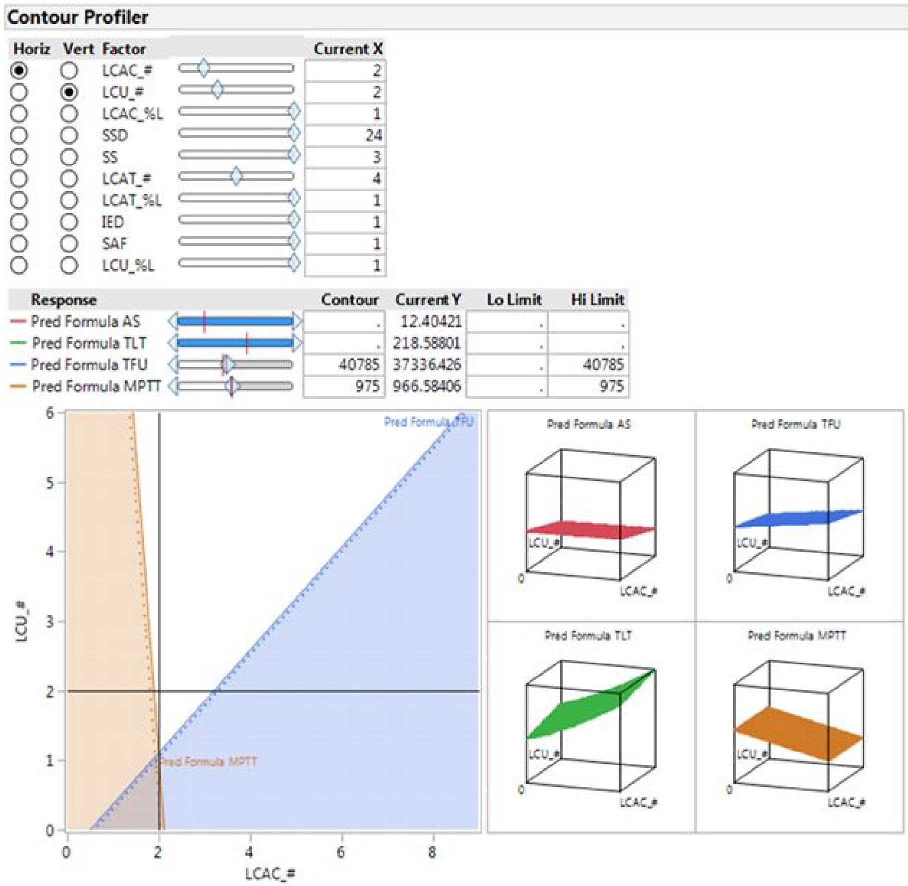


Figure 28. Scenario #6 Solution Space Contour Plot

Next, the solution space contour plot was updated with the limits for both TLT and AS. The plot was evaluated to determine whether either of these responses failed to meet operational effectiveness based on the applied limits. That contour plot was titled “Solution Space with TLT and AS Contour Plot.” Last, the contour plot that identified the limiting response was captured with the title “Limiting Response Contour Plot” which showed where the SSD and SS solution space failed to fall within the limits. There were a few cases where multiple solution spaces existed, for a SSD of 18 with a SS of two, and a SSD of 24 with a SS of one. For these instances a second solution space plot was

provided for the SSD of 24 with a SS of one. This methodology was employed for all 27 scenarios and resulted in 81 contour plots shown in Appendix H.

Analysis of all these contour plots was completed for all 27 three-ship ARG scenarios, and the resulting insights and observations were compiled into the scenario analysis shown in Figure 29. This analysis summary shows the maximum SSD and SS for each scenario, the limiting response if the scenario did not have solution space for all combination of SSD and SS, whether the scenario meet the TLT limits, and whether the scenario met the AS limits. Three scenarios (highlighted in green) had solution space for all combinations of SSD and SS: Scenario 6, Scenario 21, and Scenario 27. All three scenarios were comprised of the LCAT which had performance parameters in-between the LCU and LCAC. This identifies the need for a third connector that is faster than the LCU, but also has an energy efficiency better than the LCAC. One of the reasons the LCAT was chosen was because of the catamaran hull shape allowing for less drag and increased hull speed, resulting in a better fuel efficiency than the traditional hull types. The data suggests a platform with these hybrid performance parameters would provide an advantage across the broad utility of missions required of U.S. Navy connectors.

Scenario Analysis								
Scenario Configuration				A. Maximum Value While Maintaining Operational Effectiveness		B. Limiting Response For A	C. Does the scenario still meet operational effectiveness when limits were added for the following?	
Scenario #	LCU	LCAC	LCAT	SSD	SS	MPTT/TFU	TLT	AS
1	6	0	0	18	2	MPTT	yes	no
2	3	4	0	24	2	MPTT	yes	yes
3	3	0	4	24	2	MPTT	yes	no
4	5	2	0	18	3	MPTT	yes	no
5	2	6	0	24	1	TFU	no	yes
6	2	2	4	24	3		no	yes
7	5	0	1	18	2	MPTT	yes	no
8	2	4	1	24	2	MPTT, TFU	yes	yes
9	0	3	5	24	2	TFU	no	yes
10	4	3	0	24	1	MPTT	yes	yes
11	1	7	0	24	1	TFU	no	yes
12	1	3	4	24	2	TFU	no	yes
13	3	5	0	24	2	MPTT, TFU	no	yes
14	0	9	0	18	2	TFU	no	yes
15	0	5	4	(18, 2) , (24, 1)	(18, 2) , (24, 1)	TFU	no	yes
16	3	3	1	24	2	MPTT	yes	no
17	0	7	1	(18, 2) , (24, 1)	(18, 2) , (24, 1)	TFU	no	yes
18	0	3	5	24	2	TFU	no	yes
19	4	0	3	24	1	MPTT	yes	no
20	1	4	3	24	2	TFU	no	yes
21	1	0	7	24	3		no	yes
22	3	2	3	24	2	MPTT	no	yes
23	0	6	3	(18, 2) , (24, 1)	(18, 2) , (24, 1)	TFU	no	yes
24	0	2	7	24	2	TFU	no	yes
25	3	0	4	24	2	TFU	yes	no
26	0	4	4	24	1	TFU	no	yes
27	0	0	8	24	3		no	yes

* Note: Low and High Limits Based on Response Surface Distributions (75% Quartile for High, 25% Quartile for Low)

Figure 29. Scenario Analysis

The TLT analysis identified that most scenarios did not meet operational effectiveness even when both MPTT and TFU limits were met. This suggested that operational tactics could be employed to reduce the TLT. Tactics such as staggering the connectors at the onset and coordination of the reloading by varying the speeds of the connectors during the operation could be employed to minimize loitering. Evaluation of this could be accomplished by upgrading the model to include speed power curves for all connectors and developing an algorithm to slow the approach of a given connector if a connector is confirmed to be in a reloading condition.

Additionally, the AS response did not meet operational effectiveness when the scenario included at least three LCUs. It is believed that most operational scenarios will need to be completed in a timelier manner, resulting in the need for the AS to be at least within the limits identified in this capstone report. This identifies that the hull speed capabilities of the LCU are inadequate when compared to other connectors.

The solution space shown in the contour plots provided the data necessary to draw conclusions on key design parameters, the best combination of factors to satisfy the seabase-to-shore MOE, and alternatives to present to the stakeholder. Analysis of all the plots and data provided the information required to gain insight and draw the conclusions necessary to answer this capstone project’s research questions. The modeling, simulation, and statistical analysis tools used in this capstone project were provided to the advisors and the E2O energy office to further analyze any of the given scenarios, or expand the analysis for new capabilities and parameters should the need exist. This systems engineering analysis can be iteratively repeated as necessary to define new solutions to ever-changing mission parameters.

B. SHORE SITE SUSTAINMENT

The shore site sustainment portion of the study was conducted after the MEU had transferred to shore and established a MAGTF command element. The capstone team used the MAGTF Power and Energy Model (MPEM) software to evaluate energy and fuel usage of the MEU. This software is used by the Marine Corps to increase MAGTF energy efficiency and self-sufficiency by evaluating an operational power demand and

evaluating the best energy alternatives to supply it. MPEM was used to evaluate the power consumption of the MEU, while research was conducted on both traditional and alternative energy sources to meet this demand. In addition to the evaluation of sustainable sources, the capstone team identified commercially available military grade solutions. The following is a list of alternative energy sources that could potentially meet this objective: diesel, FlexGen, wind, solar, and wave. Criteria were developed to evaluate these alternatives and determine what was most feasible for use in the field. From this, the top three alternatives were evaluated against USMC renewable energy goals as outlined in the USMC Expeditionary Energy Strategy Implementation Planning Guidance to determine the number of alternative energy systems that would be needed to meet this requirement. This provides several options for the E2O office, based on the use of three different technologies, to meet renewable energy goals for similar operational scenarios.

1. Shore Site Simulations Functional and Physical Architecture

The sustainment portion of the simulation use MPEM, a different software tool that better fits the analysis done at the shore site. The sustainment portion was studied to obtain information that would indicate renewable energy can be used. The function "Sustainment" in Figure 30 shows the utilization of the MPEM software tool. The sub-functions required for proper operation include initializing the parameters, constructing the organization, the scenario, the reports needed, and obtaining results. The MPEM tool allows each function to be conducted and was captured in the architecture. These functions are needed to complete the sustainment portion of this capstone project's scenario. Each of these sub-functions has been decomposed further and is shown in Appendix A.

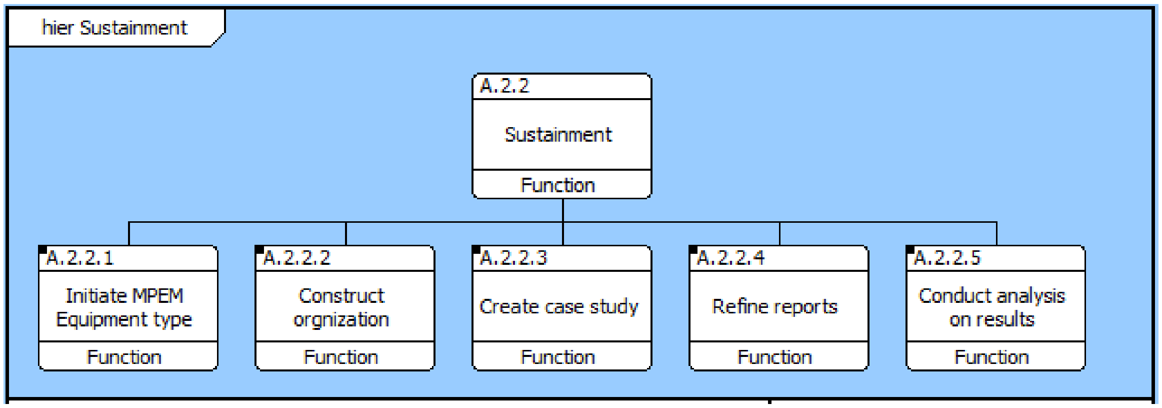


Figure 30. Breakdown of Function "Sustainment"

The decomposition of the top-level function helped discover most, if not all of the functions needed to complete the study. The simulation decompositions helped break out the steps on how to conduct the simulation effort. In addition, it helped understand how to breakdown both the "seabase-to-shore" and the "sustainment" efforts. The architecture selected helped correlate the simulation effort with the USMC operations. After the decomposition of each function was established, understanding how each sub-function relates to another provided addition information for simulation.

The relationships of the function "Sustainment" can be seen in Figure 31, which shows the initiation of the MPEM simulation software. The first step within MPEM was to initiate the equipment list of the MEU and its organization at the command site. The input requirement for the model includes the location and temperature information of the scenario. In order to extract the results, a report format was constructed that is compatible with the analysis software tool, and the results were analysed for the sustainment effort using renewable energy sources that best fit the warfare environment. The results of the model were analyzed to see the potential use of renewable energy sources.

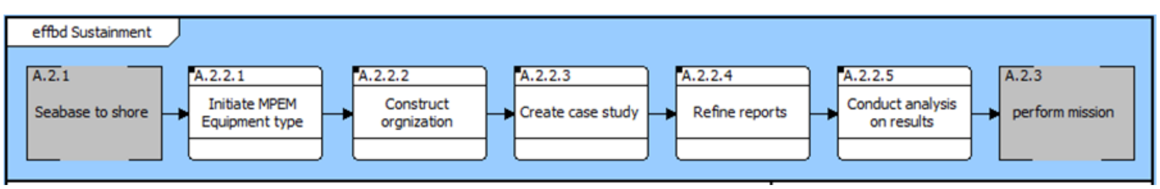


Figure 31. Sustainment Functional Flow Block Diagram

As shown in the previous figures, each function was related to the software tool used in the simulation which helped to create the steps needed to run the simulation models. Additional steps for each function can be seen in Appendix B, for the purpose of this report, only the overview functions were shown. The architecture shown was the final layout that was used to complete this capstone effort. Initially, there was a lot of rework performed on the architecture as it was refined through the process. Overall, this architecture helped find the path to get significant results needed to answer the research questions.

2. Identification of Shore Site Power Alternatives

Several technologies were explored, analyzed, and evaluated to determine whether the MAGTF energy footprint could be reduced, while still maintaining operational effectiveness. Feasible alternatives were identified to reduce the use of fossil fuel generators by deactivating or eliminating them from the MAGTF equipment, thereby reducing the sustainment cost of an expeditionary force.

Solar panel technology capabilities have increased in the recent years and are now found in opaque and flexible forms. This opacity allows for a much higher collection of light and therefore a significant boost to efficiency while also providing a significantly less conspicuous product. This change in reflectivity and use of a silent energy production medium allows MAGTF forces to remain less conspicuous to enemy forces. Conex cargo box sized solar panel systems have been developed that can provide up to 15kW of power, such as the ECOS PowerCube shown in Figure 32. Multiple PowerCubes could be used to produce the amount of energy desired.

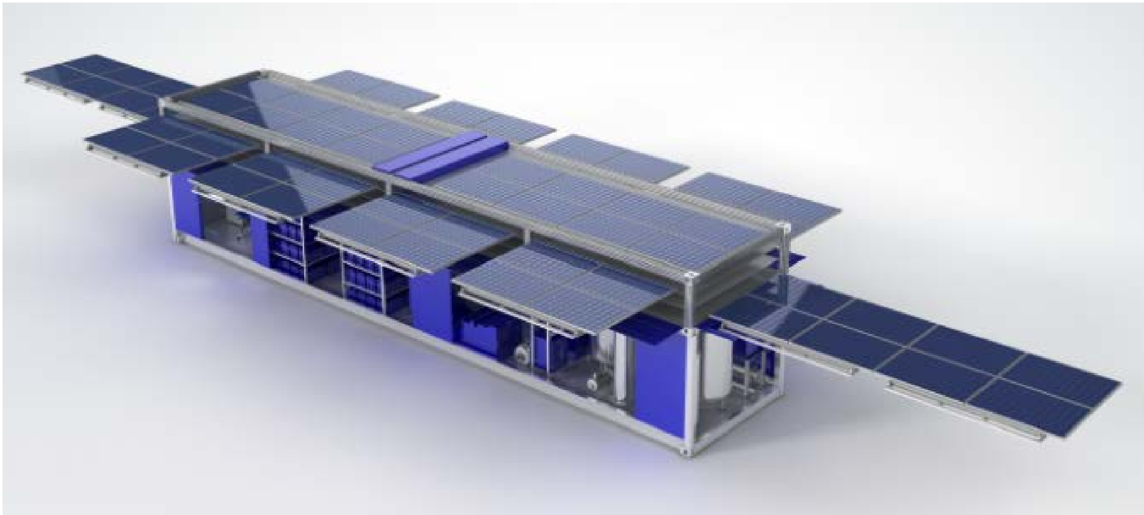


Figure 32. PowerCube Conex Box. Source: The Skeptics Guide to the Universe, www.theskepticsguide.org/solar.

Additionally, this capstone team identified a newly developed solar panel system that unrolls from a tow-behind cargo cube. This system, called the Roll-Array Multi-Gen by Renovagen, can be scaled up or down depending on the amount of available space for the solar panels to lie out, and can be easily stowed and transported alongside the rest of the MAGTF equipment. As seen in Figure 33 this solution is also comparable in size, when rolled up, to the diesel generator systems currently in use.

Figure 33. Roll-Array Multi-Gen. Source: Renovagen at Renovagen.com.

Wind energy has drastically improved over the last decade and is capable of producing much more power than other sustainable technologies. Conex box size systems, as shown in Figure 34, have been developed by Uprise Energy to produce 50kW of electric wind power in a portable and stable fashion. Combined with the prevailing tidal winds, a nearly constant, low cost energy source could be added to the expeditionary forces, allowing the shore-site fuel footprint to reduce appreciably.

Figure 34. Uprise Energy Portable Wind Generator.
Source: Futuristic News, futuristicnews.com.

Wave generators can provide a constant stream of electricity in a nearly silent fashion, further reducing the likelihood of detection by enemy forces. While there are four main types of wave generators, only attenuators and point absorbers were explored in this study due to their ability to be towed behind sea-based platforms. The theory of operation is to use the motion of the waves to actuate hydraulic cylinders that turn hydraulic motors that power electrical generators. Although this technology has matured somewhat in recent years, commercial off-the-shelf solutions are not as readily available and reliability over long periods is unknown. Further evaluation will need to be

conducted to identify a specific solution should this alternative need to be further explored. For the purpose of this capstone project, the system evaluated for the wave attenuator was the Pelamis Wave Machine, Figure 35, and the system evaluated for the point absorber was the Ocean Power Technologies PowerBouy, Figure 36.

Figure 35. Pelamis Wave Machine. Source: REUK, http://www.reuk.co.uk/OtherImages/pelamis2.jpg.

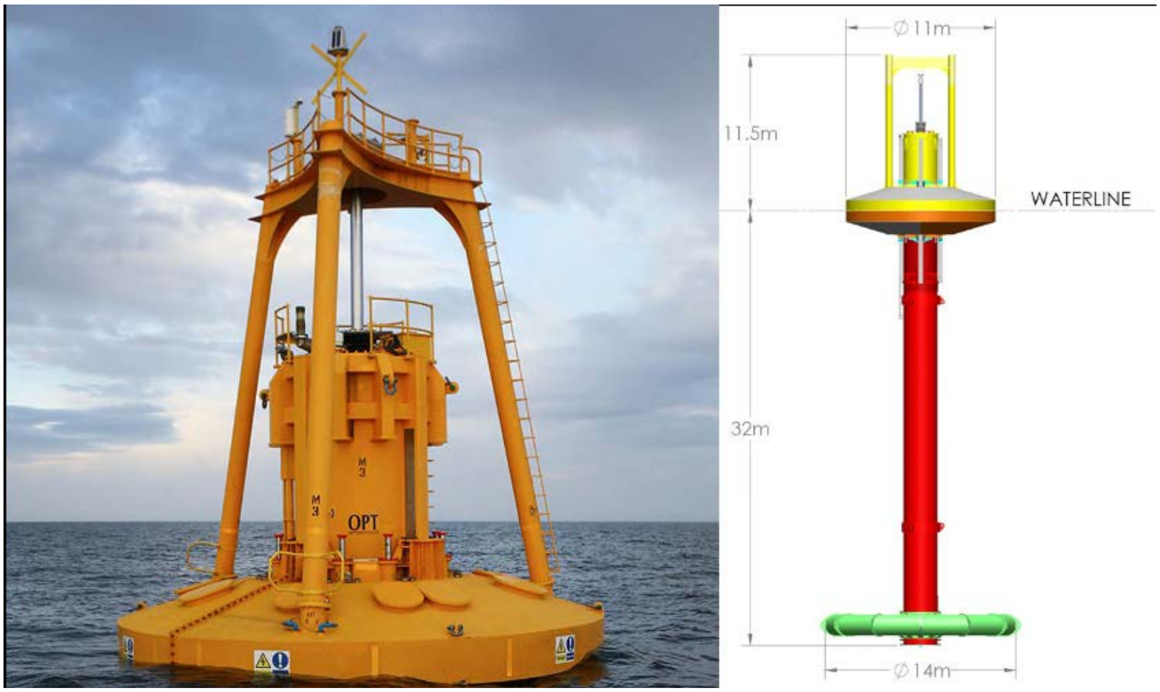


Figure 36. Ocean Power Technologies PowerBouy. Source: The Switch Report, www.theswitchreport.com.au.

Hybrid technology that utilizes both liquid fuel and renewable energy sources can be used as a medium before going fully independent of liquid fuel. Currently there is a system called FlexGen, Figure 37, that is commercially available and has shown the possibility of this technology. FlexGen uses a diesel generator in conjunction with other energy sources to generate on-demand electricity for the forces as needed. FlexGen has energy storage capabilities that allow for optimization of energy efficiency by only powering traditional generators when that power capacity is needed. It also has the ability to toggle between different renewable energy sources to obtain the electricity needed, for lower power consumption loads and times of peak power usage. While alternative energies such as solar panels are maturing, FlexGen has become more of a manager amongst all available energy sources. Meaning that other energy sources such as wind or water can be integrated to be used with the FlexGen. Of course, cost increases, but FlexGen allows the force to take advantage of the alternative energy sources as their availability increases.

Figure 37. FlexGen Power System. Source: Early Energy, www.earlenergy.com.

3. Evaluation of Shore Site Power Alternatives

Many renewable energy sources have matured to the point that they may be viable enough to be used in a battlefield environment. Wave generation was further broken down into wave point absorber and wave attenuators. These energy sources were evaluated using criteria that best portrayed the desired capabilities needed for a USMC mission. An Analytic Hierarchy Process (AHP) was then conducted with the defined criteria to evaluate these energy sources and determine the top three sources that should be further pursued. The AHP provided a quantitative technique to defensibly compare the alternatives

When conducting the AHP analysis, the capstone team compiled a list of criteria which were applicable to all technologies studied. The criteria are defined in Table 7 and were ranked according to importance for each renewable energy source based on the commercially available military grade system associated with it. The scale selected for ranking was four levels, with green being the best and dark red the worst. After thorough research in support of this effort, the capstone team made independent rankings for each alternative energy systems for all eight criteria. The rankings shown in Table 8 are the results of capstone team's consensus from the research conducted. The Power Generation criteria would relate to a quantity value which would be provided to the function "Initiate

MPEM Equipment Type." These same criteria would correlate with the output of the MPEM module electricity generation report analyzed in the "Conduct Analysis on Results" function. The criteria selected were used to compare the energy sources to the diesel generator which is the current technology used by the military.

Table 7. Criteria Definitions

Criteria	Definition
Reliability	"that characteristic of design and installation concerned with the successful operation of the system throughout its planned mission and for the duration of its life cycle" (Blanchard and Fabrycky 2011, 112).
Power Generation	the ability to service the electricity demand to support an MEU operation.
Maintainability	"that characteristic of design and installation that reflects the ease, accuracy, safety, and economy of performing maintenance actions" (Blanchard and Fabrycky 2011, 112).
Supportability	"that characteristic of design that ensure that the system can ultimately be serviced and supported effectively and efficiently throughout its planned life cycle" (Blanchard and Fabrycky 2011, 112).
Form Factor	being portable and small in size.
Renewable Energy	energy sources which have no limited quantity.
Feasibility	being suitable for being used in a military operation/ environment
Cost	the amount that the government would pay for the product.

Table 8. Criteria and Levels for Each Renewable Energy Source

Rank	Evaluation Criteria:	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuat or
1	Power Generation (kW to support demand)						
2	Maintainability						
3	Supportability						
4	Renewable Energy						
5	Reliability						
6	Feasibility						
7	Form Factor (Weight and Size)						
8	Cost						

Best	Mid	Low	Worst

As the table shows, the wave point absorbers and wave attenuator technologies were too premature to be fielded solutions. Additionally, it was expected that the diesel generator, a historically proven solution, would receive favorable ratings for all but the renewable energy criteria. Appendix I shows the entire AHP analysis in detail, including the priority vectors used for the AHP analysis. The priority vectors are the weights (expressed in a percentage) associated with each criterion based on mission objectives. The criteria for this analysis were ranked to the USMC expectations as shown in Table 9

Table 9. Criteria Ranking

Criteria Ranking Normalized	Priority Vector
Reliability	33%
Power Generation	23%
maintainability	16%
supportability	11%
Form Factor	7%
Renewable Energy	5%
feasibility	3%
cost	2%

The results from the AHP analysis shown in Table 10 are in agreement with the rankings in Table 9. The AHP provided a quantitative evaluation of the energy sources with which to identify a promising solution to meeting E2O energy goals. Even though the results identify that the diesel generator is overall still superior to the current renewable energy sources, it also identified the best renewable energy source as wind, with solar and FlexGen being second and third respectively. As expected, the wave attenuator and waypoint absorber had the lowest ranking and were dropped when conducting further analysis. The top three alternative energies, in this case wind, solar, and FlexGen were selected for further analysis in MPEM.

Table 10. AHP Results

Criteria	AHP Result
Diesel Generator	28%
Wind	21%
Solar	19%
Flex Gen	18%
Wave Attenuator	8%
Wave Point Absorber	7%

4. MPEM Modeling, Simulation, and Analysis

After conducting the AHP for the feasibility of each technology, further analysis had to be conducted to see whether the alternative energies could offset traditional power generation. MPEM was a great tool to start with since it fit into the sustainment scenario described in Chapter III. MPEM is "an equipment energy-/fuel-demand-based model that captures the complex interrelationships between liquid fuel and its conversion into electricity, and enables comparison of MAGTF energy demand given different equipment sets and/or different levels of efficiency within specific equipment portfolios or individual end-items" (CMC 2013, 11). MPEM accepts as inputs: climate data, security posture, efficiency conversions, and controls. The MPEM outputs show the electricity demand and liquid fuel consumption. To set up the capstone project's scenario in MPEM, a few assumptions had to be made. The capstone team assumed that the information was accurate for the scenario location. The team also assumed that the historic MEU setup found within the MPEM, including the organization and location of the MEU, was correct, and used that setup to explore the energy demand and fuel consumption. The MEU from the MPEM model was assumed more accurate than the derived MEU model created by the team.

In addition to finding the MEU fuel consumption using traditional diesel generators, the MPEM model was used to analyze how much energy was produced using the top three alternative energy sources identified in the AHP. Utilization of these renewable energy sources is critical to meeting the USMC Expeditionary Energy Strategy Implementation Planning Guidance. The guidance identifies a 50% increase in operational energy efficiency, a 50% decrease in fuel consumed by a Marine each day, and projects a resultant "decreased demand for logistics support, particularly for liquid fuels" (USMC n.d.-b, 21). The guidance indicates this decrease is in response to U.S. Government "mandates for reduced energy and water consumption and increased use of alternative energy," with the ultimate goal "50 percent of our bases and stations will be net zero energy consumers by 2020" (USMC n.d.-b, 21). In addition, the planning guidance provides efficiency gain goals for utilizing renewable energy sources. The "Meet Operational Demand with Renewable Energy" shown in Figure 38, set goals of

25% for 2015 and 40% for 2020 (USMC n.d.-b, 22). Extrapolating a curve to these data points for 2016 identifies a renewable energy goal of 28%. This project's objective for the analysis of renewable energy sources directly addresses that goal by providing a recommended combination of renewable/alternative energy sources to replace the traditional generators.

E^2 GOALS	Efficiency Gains		
	2015	2020	2025
Embed E^2 Into USMC Ethos			
Lead and Manage E^2	25%	40%	50%
Increase Energy Efficiency of Weapons Systems, Platforms, Vehicles, and Equipment			
Meet Operational Demand With Renewable Energy			
Reduce Energy Intensity (EISA 2007)	From 2003 to 2015, reduce energy intensity at installations by 30%		
Reduce Water Consumption Intensity (EO 13514)	Through 2020, reduce water consumption intensity by 2% annually		
Increase Renewable Facility Energy (NDAA 2010, SECNAV)	By 2020, increase amount of alternative energy consumed at installations to 50%		
Decrease Petroleum Consumption (SECNAV)	By 2015 decrease non-tactical petroleum use by 50%		

Figure 38. E2O Objectives and Goals

The MPEM model was run using a new equipment library entry the team created for MPEM. The three alternative energy sources added to the library were a solar panel system by ECOS PowerCube which generated 7kWh of power, a wind generator system made by Uprise Energy which generated to 50 kWh, and the FlexGen system from Earl Energy which produced 35 kWh. Figure 39 shows the three new library entries for the top

three alternative energy sources identified in the AHP. The MPEM model and associated library entries were provided to the E2O office for further evaluation at their discretion.

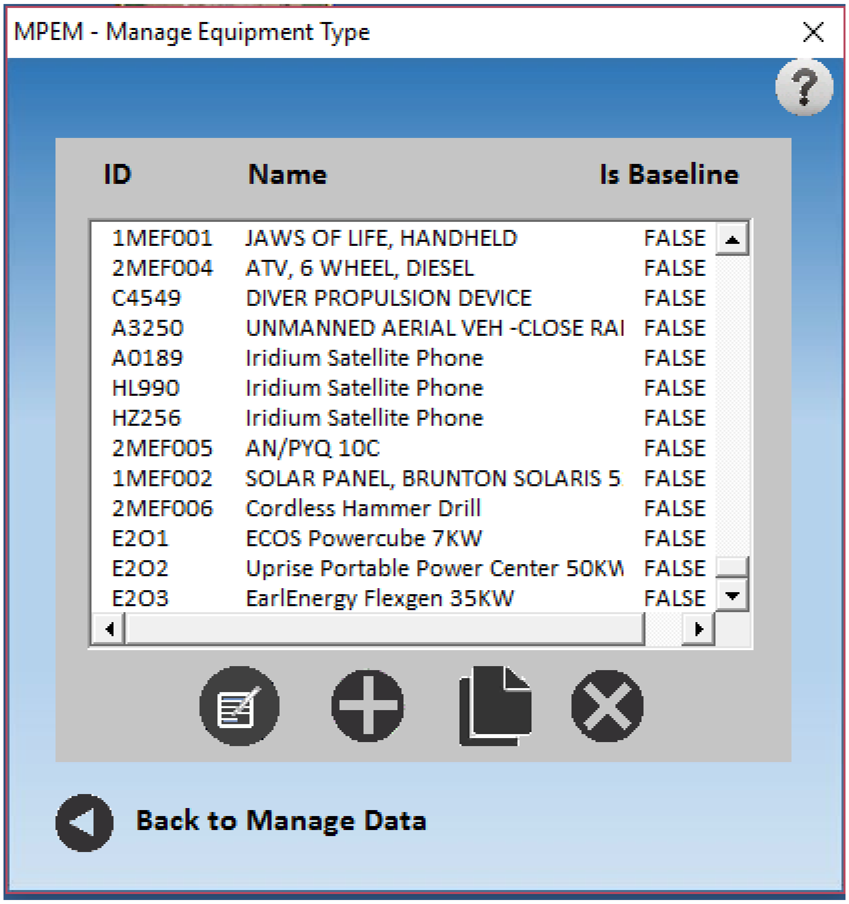


Figure 39. Equipment Database with Added Entries

This scenario was run for three days using the historic MEU and the newly added library entries for the alternative energy sources. The scenario prescribed by the capstone team identified three days as the typical amount of time required to execute the seabase-to-shore transit, and therefore the sustainment portion of this capstone project. For this evaluation, only one of each alternative energy system was included in the scenario. This provided the total energy produced by a single unit over the course of the three-day scenario, which could be scaled up to meet the USMC renewable energy goals. More detailed information on setting up the report on MPEM can be seen in Appendix A. Understanding the USMC's electricity demands gave the team a good estimate of the

replaceability of the traditional energy sources with alternative sources while maintaining the USMC's needs and meeting their renewable energy goals.

Table 11 shows how much electricity the MEU demanded, how much electricity each renewable source generated, and how much electricity a typical diesel generator produced. The output data shown in the table are related by days.

Table 11. Electricity Demanded and Generated per System

Electricity demand/generated	KW/D
MEU	8634.5
Solar systems	80.5
Wind generators	1200
FlexGen systems	822.5
Diesel generator	1440

The analysis done within MPEM showed that some of the diesel generators in the MEU should be replaced with renewable energy sources. Taking the results from Table 11 and the renewable energy goals of the E2O, calculations were performed to identify the feasibility of the renewable energy alternatives. Table 12 shows how many units are needed for each renewable energy source to support the fossil fuel reduction as determined by the renewable energy goals from 25% to 40%, as seen in Figure 38, at the end of FY 20. From this analysis, the wind generator and the FlexGen System showed the greatest impact on fossil fuel reduction using renewable energy sources. Even though solar technology is growing rapidly, the results of this analysis showed that its power generation capabilities are not sufficient for large scale power generation in the warfare environment. It is interesting that a review of the most recent E2O Programs of Record (POR) utilize solar power.

From this evaluation, the wind generator produced the most electricity to support the MEU, but is highly dependent on wind (weather conditions) being present. The

FlexGen System was the most balanced between renewable energy and fossil fuels, but still has its roots in traditional generator based power. Depending on the application, either the Uprise Energy wind generator or the Earl Energy FlexGen would be the best choices to meet current E2O energy goals. Increasing power generation from sustainable sources has many benefits, including decreasing the logistics infrastructure, saving time and manpower in fuel transport, reducing the susceptibility of the MEU due to decreased dependence on the logistics supply chain, and supporting additional mission payload transfer. With this in mind, the rationale exists to further pursue these two alternative energies for additional evaluation. Based on the data, it is anticipated these technologies could supplant solar and potentially become a POR.

Table 12. Units Needed to Meet Energy Demand

FY	15	16	17	18	19	20
(%) Renewable energy goal	25	28	31	34	37	40
Solar systems	27	31	34	37	40	43
Wind generators	2	3	3	3	3	3
FlexGen systems	3	3	4	4	4	5

V. CONCLUSIONS

This chapter was broken down into four sections that include the responses to the research questions, areas of further research, conclusion, and recommendations. The research questions were answered succinctly and are supported by the data and analysis presented in this study. Further research areas were documented to pass on ideas to future capstone teams and were inspired by discussions with the stakeholders and advisors while establishing the boundaries for this study. The conclusion is supported by the analysis and represents input from all team members contributing to this capstone project and the recommendations were developed while the team discussed the results of this study. Additional information is provided in the sections that follow.

A. RESPONSE TO RESEARCH QUESTIONS

This study framed three research questions to be explored for both the seabase-to-shore maneuver and the sustainment operation at the shore site portions of the ship-to-objective maneuver (STOM). The capstone team used Model Based System Engineering (MBSE), modeling and simulation (M&S), and statistical analysis to define, capture, evaluate, and explore alternatives to maximize throughput and energy efficiency. Research questions one and two evaluate the best combination of connectors for the seabase-to-shore maneuver. The team evaluated performance characteristics of three surface connectors to determine which were critical to mission success and which could potentially be further pursued in the future. The results of the analysis identified that both material and non-material solutions exist to improve the energy efficiency of the operations while maintaining operational effectiveness. Research question three evaluated several commercially available alternative energy technologies that implement energy efficiency goals during the sustainment portion of the operation. M&S efforts were conducted to gain insight into the amount of energy required to meet these goals and the number of alternative energy systems needed to supply that power.

1. Research Question One

How does the selection of seabase-to-shore connector type affect the throughput and energy efficiency of the seabase-to-shore operations of a STOM in an A2/AD threat environment?

Three seabase-to-shore connector types were evaluated in this capstone project: the LCAC, the LCU, and the LCAT. These connectors were organized into 27 preconfigured groups (or scenarios) that are typically within the capabilities of a three-ship ARG. The ships have known size and weight constraints that limit the numbers of connectors that can be carried by a single ship, and the connector combinations that can physically fit within the well-decks of the ships. The M&S and statistical analysis efforts were conducted using these 27 scenarios and resulted in three that meet both operational effectiveness and energy efficiency criteria as outlined in Chapter IV.A.7 of this capstone report. The three scenarios were as follows:

1) Scenario #6: 2 LCU, 2 LCAC, 4 LCAT
2) Scenario #21: 1 LCU, 7 LCAT
3) Scenario #27: 8 LCAT

These combinations of connectors were evaluated for both a variety of seabase standoff distances (SSD) and sea state (SS) as directed by the USMC Expeditionary Energy Office (E2O). This wide range of environmental conditions and the ability to complete this mission in an A2/AD threat environment identified that for this operational scenario that these connector combinations would be suitable for a broad utility of missions.

One commonality that was identified in each of these scenarios is that each one contained at least four LCAT connectors. The 75% quartile for mission payload transfer time (MPTT) and total fuel used (TFU) were established as limits for the scenarios. Based on these limits, the LCAT's maximum speed and the LCAT's energy efficiency – which is an increase over the LCU, and an increase over the LCAC respectively– provided an acceptable hybrid performance. These are key components to providing the throughput and energy efficiency to complete all combinations of SSD and SS. Since a

connector with these performance parameters does not currently exist in the U.S. Navy, this capstone report identifies the need for the LCAT or a similar platform of this type.

Initially this capstone project looked to provide a conceptual design for the replacement of the LCU using an alternative landing craft (ALC) with a new electrically powered LCU-like design. The ALC looked to utilize a catamaran hull design with bow ramp for "splash capability," be fabricated with lightweight composite material with topside armor, have steerable bow thrusters with compressed air blasts, and a payload that reduced the 1000 horsepower powertrain requirement of the incumbent LCU. This capstone team selected the LCAT due to difficulties identifying the performance parameters associated with the ALC hull design, the type of engine, and the number of engines required to appropriately power the ALC. This newer design contained enough of the ALC properties to show a proof of concept, but had the known performance parameters of a craft that was already in service thereby alleviating the challenge of a conceptual design. The LCAT is utilized by the French Navy who participated in the "Bold Alligator" joint exercise in 2012, where the U.S. Navy was able to evaluate this platform in a tactical scenario. Research identified that the LCAT had all the attributes of a seabase-to-shore connector, with the additional incentive of an articulating deck that could be lowered for roll-on/roll-off activities in support of amphibious operations. The results of this capstone project show that a platform with these performance parameters would provide an increase in both throughput and energy efficiency. Further research could also be conducted to ascertain whether the initial concept of using electric motors would be a feasible solution now that electric motor technology is currently being used in commercial applications. This electric motor technology would be based on a recharge concept of operations using shore site battery recharging stations with spare batteries at the seabase,

In addition to the ALC findings, the statistical analysis of the DOE results provided several insightful findings. The statistical analysis identified that most of the scenarios did not meet operational effectiveness for TLT even if they did for both MPTT and TFU. Based on the 75% quartile limits chosen this means that a substantial amount of time was spent loitering, specifically waiting for a well-deck. This suggested that

operational tactics could potentially reduce the loiter time of the connector which in turn increased energy efficiency. Tactics such as staggering the connectors at the start of the STOM and the coordination of connectors and their approach speeds during the STOM could be utilized to minimize loiter time. Evaluation of this could be accomplished by upgrading the model to include speed power curves for all connectors and developing an algorithm to slow the approach of a given connector dependent on the locations and status of other connectors.

The statistical analysis also identified that the connectors' average speed (AS) failed to meet operation effectiveness for most scenarios containing at least three LCUs even if successful for both MPTT and TFU. This provides rationale to suggest that the hull speed capabilities for the LCU do not provide enough speed to be effective when compared to other connectors. The data suggests that using a new hull design, possibly a catamaran style such as the LCAT, could be effective at improving the overall speed of the STOM.

The statistical analysis also identified a second combination of connectors for the seabase-to-shore maneuver through the use of the maximize desirability function in the prediction profiler. When the response surface limits were entered in the desirability function, the maximized desirability returned a combination of connectors consisting of five LCACs, with no LCUs or LCATs. The capstone team evaluated all four responses for these limits and determined that when all factors were set at their most desirable settings, the LCAC was the connector of choice. The analysis of each response identified that the TLT was increased as the number of LCACs was increased. Since the maximize desirability treats all response surfaces with equal weighting, the optimal number of LCACs was determined to be five. This provides insight into an environmental setting that would be more open to greater fuel usage since the limits were not changed to reflect the closer SSD and lower SS. This suggests that the maximum speed of the LCAC has a tactical advantage when energy efficiency is not as stringent, thus emphasizing the need to improve the overall speed of the LCU.

2. Research Question Two

What operational, tactical, and environmental factors have a statistically significant effect on the energy efficiency of the seabase-to-shore portion of seabase operations?

This capstone project used the MPTT and TFU as the two primary responses for the seabase-to-shore operational scenario. During the statistical analysis, the capstone team created a sorted parameter estimates plot in JMP Pro for both MPTT and TFU to identify what factors have a statistically significant effect for these responses. Specifically, the sorted parameter estimates plot showed the positive and negative influence of the factors on these responses in addition to their significance. According to the results that were obtained from the sorted parameter estimates plots, the three factors that have the most statistically significant effect for both MPTT and TFU are the SSD, the SS, and the number of LCACs. However, the capstone team also identified that factors such as the increased loading rate (Time Loading) for the connectors, rocket propelled grenade (RPG) threat, improvised explosive device (IED) threat, and small-arms fire (SAF) threat were not statistically significant for the MPTT and TFU. Additionally, the team noticed in the sorted parameter estimates plot that the number of LCACs and LCUs had a substantial effect on the seabase-to-shore operational scenario in terms of the TFU.

The number of LCACs had a positive effect in the TFU because the LCAC had the highest fuel burn rate compared to that of the LCU and LCAT. In addition, the LCAC is the fastest connector between the LCU and LCAT. However, the capstone team noticed that the number of LCUs had a negative effect in the TFU because the LCU had the lowest fuel burn rate compared to the LCAC and LCAT. Additionally, the LCU is the slowest connector between the LCAC and LCAT. This identified that in terms of fuel consumption, there is trade space to be found to reduce the TFU to a more energy efficient level, while still falling within the limits of MPTT. This potentially makes the LCAT connector very appealing with a better fuel efficiency than the LCAC and a much faster maximum speed than the LCU.

After the sorted parameter estimates plot were analyzed for the two primary responses, the capstone team proceeded to analyze the sorted parameter estimates plots. This analysis encompassed the two secondary responses of the seabase-to-shore operational scenario to see if there were any insightful findings for these responses. Specifically, this capstone project used the TLT and AS outputs as the secondary responses for the seabase-to-shore operational scenario. According to the sorted parameter estimates plot for TLT, the SAF threat had the highest significance whereas the other parameters contributed to the delays and queuing at the well-decks. However, according to the sorted parameter estimates plot for AS, the number of LCACs, the number of LCUs, SS, and SSD had the highest significance. The team identified that the speeds for LCAC and LCU are on the far opposite ends of each spectrum. Additionally, the capstone team noticed that there is a trade space for a solution in the middle that could be faster than the LCU and provide better fuel efficiency than the LCAC.

During the statistical analysis, the capstone team also looked to identify if there were second order terms that were significant for these responses. According to the sorted parameter estimates plot for the TLT. Specifically, second order terms such as the interaction between the number of LCATS with the LCAT percent loading and the number of LCACs with the LCAC percent loading contributed to the increase in TLT for the seabase-to-shore operational scenario. However, the team noticed in the sorted parameter estimates plot for the AS that the number of LCACs times the LCAC percent loading had a negative effect in the AS. During the analysis of the sorted parameter estimates plots, this capstone project found that the LCAC percent loading was significant for both primary and secondary responses.

According to the sorted parameter estimates, the LCAC percent loading had a positive effect in the TLT and a negative effect in the MPTT, TFU, and AS. This result suggests that there is a potential tradeoff between these four responses based on the mission requirements for the seabase-to-shore operational scenario. The prediction profiler was used to further investigate the effect of the LCAC percent loading in the four responses by showing that increasing the LCAC percent loading reduces TFU. This is due to the fact that there would be fewer round-trips to shore but this approach increases

the loiter time and reduces the average speed of the connector. During the statistical analysis, the team also identified that the desirability in the prediction profiler was maximized for values of 80% and 90% for the LCAC percent loading. Specifically, this capstone project noticed that values of either 80% or 90% for the LCAC percent loading are the optimized solutions to maximize the benefit for MPTT and TFU, while minimizing TLT and maximizing AS. Since MPTT and TFU were the primary responses, an LCAC percent loading was selected at 100% because this was where the MPTT and TFU were best minimized. TLT and AS were viewed as secondary objectives.

3. Research Question Three

Which possible technologies will enhance energy efficiency, while maintaining operational effectiveness and success, during the sustainment phase of the operation?

Renewable energy sources have been maturing rapidly and show promise for the use of these technologies in a warfare environment. After conducting market research to see what is available, many interesting technologies are emerging. They cover from using light, air, water and other natural sources to be converted into clean electricity. It was found that solar panels, wind generators, and FlexGen Technologies were best suited to for military applications in a number of different environments. These three technologies are available to be purchased as commercially available products yet are not yet fully tested under military standards.

When analyzing the renewable energy sources, the criteria were set to compare with the system that is currently used. Currently the military uses diesel generators to support all activities in the MAGTF command element. As previously shown in the sustainment simulation section, the top three renewable energy sources met a majority of the criteria set. Initially, the solar power system appeared to be the best, but did not produce the power generation needed to support the MEU in sustainment. The system was not ruled out because it could have applicability which depended on the tactical situation and its high technical readiness level.

The other two systems, FlexGen and wind, had the power generation needed to support the force, yet the technical readiness level was not as high as the solar or diesel

options. The capstone team studied these renewable energy sources because of portability and adaptability to a command site. Some of the other energy sources explored were too bulky and not sufficiently portable. The capstone team determined that the wave point absorber and the wave attenuators, though very clean energy sources, were high risk for all evaluated criteria. The wind generator system has been used in the field, but little was known as to whether it had supported a military operation nor whether its size is feasible in an operational scenario. Currently, the FlexGen System has been use in theater and has shown positive results in military operations.

In conclusion, there were many possible technologies that could have been used as an alternative to liquid fuel. This analysis identified that diesel generators are the most mature technology, but are also the least clean. A hybrid type technology such as the FlexGen, takes advantage of both technical maturity and clean energy storage and production when available, while maintaining the ability to use liquid fuel if needed. Wind generators produce 100% sustainable energy and produce sufficient power, but are highly dependent on weather conditions. As wind generators become more mature, they may become the best sources for renewable energy due to their higher energy generation capacities. To meet the E2O goals, this capstone project has shown that all three technologies are able to support the sustainment phase of the operation while maintaining energy efficiency and operational effectiveness, and have demonstrated the criteria necessary to transition to Program of Record assets.

B. AREAS OF FURTHER RESEARCH

The capstone team noted areas of further research during meetings with the stakeholders and advisors, and discussion during the team meetings while working to develop and focus this capstone project baseline concept. The model for this capstone project can be enhanced by considering the research areas described in this section and building upon the E2O STOM model. Incrementally building upon the baseline model will reduce the number of assumptions and add more areas for energy exploration that may reveal recommendations that reduce the energy footprint typically achieved during a STOM mission.

1. Phase II Assault

This study was split into two phases. For Phase I, this capstone project, focused on developing a baseline M&S capability that executed a STOM mission under conditions described by input factors. The Phase II assault that was brought forward from a previous capstone project (Bourgeouis et al. 2015, 14) was not considered as part of this capstone project due to lack of time to learn MEU assault tactics, lack of knowledge of MEU GCE tactics, and lack of interest expressed by stakeholders. The capstone team limited the scope of this capstone project to an achievable level, and determined that Phase II would exceed this scope. Phase II of this capstone project should be further defined and discussed with the E2O stakeholders before the next team moves forward with it.

There are several areas in this capstone project that describe the scope of Phase II. As shown in Figure 7, Phase II begins on completion of Phase I with the setup, initialization, and operation of a ground based CE. The requirements for Phase II include the movement of a portion of the GCE to the FOM site located 135 NM north of the landing zone (LZ). Knowledge of GCE movement tactics and the energy required to move and sustain the combat force is required to accurately define and build upon the baseline model. The energy used while withdrawing the combat force from the FOM site may be different than the energy used to insert the combat force so this must also be considered as part of the Phase II scope.

2. Speed Power Curves and Varying Connector Speeds

Speed-Power curves for each craft are needed to improve the M&S accuracy of surface connector fuel consumption. This baseline capstone project model was constructed using state-based power estimates in lieu of continuous speed-power curves. Each connector was assumed to be operating at one of three possible fixed power states at any time in the simulation: *Off*, *Idle* and *Full Power*. The first power state, *Off*, consumes zero energy from fuel, assumed all main engines are secured, and is used while in the connectors are in a well-deck.

The second power state, *Idle*, assumed all main propulsion engines to be in an idle condition which reduced fuel use. For the LCU and LCAT idle represented propulsion engines at minimum RPM with minimum to no thrust to maintain steerage. The fuel consumption rate for this state was calculated for LCUs (Detroit Diesel n.d.) and LCATs (MTU 2011) using published fuel curves given in the engine performance specifications. The LCAC, with the ability to loiter in a hovering mode and a displacement mode, had two separate idle states that defined fuel consumption while off-cushion and on-cushion with no propulsion (Silver 1983). On-Cushion idle was used while the connector was at the LZ, during short-term A2/AD events or while loitering by the seabase waiting for a well-deck to become available. Off-cushion idle was used while the connector was loitering during a long-term A2/Ad event. Fuel consumption for these two power states was derived from published design data from Silver, with an assumed payload corresponding to the full-load condition (Silver 1983).

The third power state was *Full Power*. All connectors were assumed to operate at full power when they were moving from the seabase to the shore or vice versa. The fuel consumed at this power state for LCU and LCAC traces to the MPEM. Fuel consumption for the LCAT was calculated from the published fuel curve given in the engine performance specification (MTU 2011).

To improve model accuracy, speed-power curves need to be known for each connector type participating in the mission. This knowledge would enable fuel consumption to be varied incrementally across the factor ranges for speed, SS, and mission payload and objective. Fuel consumption should vary based on payload weight and engine power required to move the load efficiently. These curves must be defined mathematically, tested, and validated for each connector type. This effort adds considerable complexity to the baseline model and will likely have enough scope to justify a capstone project on its own.

A primary simplifying assumption in the construction of the physical architecture of the baseline model was the use of fixed speed, power, and fuel consumption values for the three surface connector craft. This was an intentional and necessary strategy to control the number of factors influencing the behavior of the model so that the complex

real-word behavior of the craft would be conceptualized in a manner that was effective for analysis. The three craft included in the analysis differ considerably in nearly every aspect of hydrodynamics, resistance and powering, main propulsion, and modes of operation. As a result, a significant number of factors are required to establish a detailed relationship for the fuel consumption characteristics at different speed, payload, and environmental conditions.

The simplest of the craft, the LCU, is a relatively basic high block coefficient displacement craft with a conventional twin screw, direct drive diesel propulsion plant. This type of craft could be adequately modeled with very few input factors, including speed and displacement, provided the speed-power curve for the craft and the fuel map for the main engines were known. Alternatively, this data could readily be estimated. The landing craft catamaran, or LCAT, while slightly more complex owing to its variable displacement hull form, could also be modeled adequately with a small number of factors based on the design documentation or suitable estimates. The LCAC, however, provides a significantly greater challenge to model adequately with the limited number of input factors that are suitable for an analysis of the type conducted. The LCAC has many different operating regimes ranging from displacement to on-cushion hover and spanning a 50-knot speed range. Its four gas-turbine engines, that provide both lift and propulsion, have widely varying fuel consumption characteristics depending on number and power output of on-line engines, air temperature, payload, thrust and lift apportioning and other factors. In order to adequately capture the wide range of fuel consumption performance and factors influencing each craft, a separate speed-power module for each craft would need to be constructed. The speed-power module could be integrated into the baseline model directly or remain an external reference that actively provided fuel consumption data to the baseline model.

The addition of this type of fuel performance module to the baseline model developed in this capstone project would provide insight to additional relationships within the ship-to-shore operation that were not possible with the abstractions made in the baseline. The primary utility of this module would be to gain insight into the most economic steaming speed for each of the craft during transit. In the baseline model, only

three states governed the speed of the connectors as they executed the STOM: idle, full-speed loaded, and full-speed light. Despite the significantly different powering characteristics of each craft, in general there is a very strong correlation between increased speed and increased fuel consumption in nearly all waterborne craft. The results of the response surface distribution in Appendix E indicate that there is a significant amount of loiter time and that the average speed of the maneuver is well below the maximum speed of fastest craft. An analysis that included speed as a controllable factor could provide insight into the relationship between craft speed and Mission Package Transfer Time with the potential to identify reduced transit speeds that have minimal effect on the mission effectiveness.

In recent efforts to optimize fuel utilization in the surface Navy fleet, reduced and optimum speed steaming has proven an effective strategy. Tools have been developed, including the Replenishment-At-Sea Planner (RASP) and the Navy Mission Planner, that operate on the premise of calculating the minimum speed (and fuel consumption) required to have a vessel arrive at its designated location "just-in-time" to meet the requirements of its plan of intended movement. This is in contrast to the more traditional "sprint-and-drift" method where the vessel transits to a location at high speed, arriving well ahead of the required time, and drifts until the designated time. The operational change has no adverse effect on meeting mission requirements and has demonstrated significant fuel savings in the surface fleet. The present operation of the craft in the baseline model has an analog behavior to the sprint-and-drift methodology. The craft are transiting at their maximum speed both to and from the seabase, and upon arrival at the sea bases are often required to loiter until a well-deck becomes available. This loiter time is a potential indication that fuel savings could be achieved, with no impact on mission effectiveness, by employing a just-in-time strategy. The suggested strategy would be for the craft movements to be coordinated to reduce transit speeds to the minimum required to arrive at the seabase just as a well-deck became available. The addition of the speed-power model to the base-line model would be required to analyze the efficacy of these types of operational changes.

3. Connector Load Optimization

During IPR number two the stakeholders expressed an interest in surface connector optimization. The example given involves matching MEU mission modules with connector types that will yield optimized seabase-to-shore transfers, thereby increasing energy efficiency and reducing fuel consumption. This interest was expressed too late in the process for the capstone team to comply with, but the team understood the value added by the request. This capstone project uses a first-in-first-out (FIFO) type queue where no consideration was given to matching connector types with mission modules to optimize their transfer to shore. The model loaded each surface connector as it arrived in the well-decks without consideration for the type, or the size and weight of the mission modules remaining.

4. Alternative Landing Craft (ALC)

This capstone project has identified that the use of the LCAT was influential in the three scenarios that were able to meet mission effectiveness for all combinations of SSD and SS. The LCAT's blend of speed and energy efficiency provides an overall performance that was much improved from the legacy connectors. The M&S results using this platform provided insight that a next generation connector should look to have attributes and performance capabilities that are similar. The LCATs use of a catamaran style hull design, was able to reduce drag, increase payload, and reduce the fuel consumption of its engines. If no additional funding was to be spent further evaluating capabilities for a next generation connector, the LCAT would be a good alternative to replace some of the current legacy systems.

As mentioned before, this capstone project had originally intended to determine whether an alternative energy connector could provide operational effectiveness. This platform, appropriately named ALC, looked to utilize alternative energies as its primary fuel source to meet E2O objectives, with little or no reduction in its capability to support mission objectives. This capstone project tried to develop a conceptualized design for an ALC to offer a potential material solution in addition to the LCAT, but did not possess the scope or expertise to accomplish this design. The idea was to generate performance

parameters for an ALC that could be input into the model and to determine whether operation effectiveness could be met.

The basic tenet of the ALC was to try and replace all of the fossil fuel craft, or as many as possible, with alternative energy craft. With the recent boom in the electric vehicle industry, electric boats are becoming increasingly capable of matching their fossil fuel counterparts. Electric motors have been designed for both speed boats and large passenger boats that would enable nearly silent and highly efficient operation. This change would allow large amounts of cargo to be brought ashore in an inconspicuous manner and may buy time for the landing forces to muster before being attacked.

A Norwegian ferry, named the Ampere, is an all-electric ferry that entered service in 2015, powered by two 450 kilowatt electric motors and fueled by lithium ion batters outputting 1000 kilowatt-hours of energy. This power plant provides sufficient power for the ferry to make 17 round trips a day for a total distance of approximately 126 miles. This distance is significantly more than the 48-mile effort that would be required for the furthest SSD explored in this capstone project. In order to have enough power for this heavy workload, the Ampere uses a recharge concept of operations utilizing quick charges during unloading and reloading and several battery swap-outs at each pier. A similar recharge concept of operations could be established for a military connector, and a realizable recharge solution could be found. Possible options include switched redundant batteries so that there would be enough power to support the mission, spare batteries that could be swapped out at the seabase, and a charging system, possibly even made up of alternative energy production systems, that could recharge the batteries at the seabase.

Incorporating design attributes such as a catamaran style hull design with bow ramp to meet "splash capability," use of lightweight composite material with topside armor, use of steerable bow thrusters, and compressed air blasts to facilitate a beach landing would provide the capabilities needed to support a broad utility of missions. Similar to the LCAT this conceptual LCU-like design could have incorporated a mobile platform that could be lowered for roll-on roll-off capability, but be raised to reduce draft

during transit. Attributes such as these would work together to provide a military capable platform with improved speed and increased energy efficiency.

An electric boat, as described herein, would also have distinct advantages to its fossil fuel counterparts. In terms of mission capabilities, it would be feasible to land advance forces in a tactically covert manner to reduce or eliminate the asymmetric forces and A2/AD environment. These forces could set up the building blocks for the expeditionary force to come ashore and may be the key to quickly establishing the MEU MAGTF as previously mentioned. Then the electric platform, or a combination of traditional and electric platforms, could bring the rest of the troops, platforms, supplies, and logistics support to the shore.

With a commercial solution being used effectively, the potential for mission capabilities to be met, a recharge concept of operations in hand, and virtually silent operation that could be a real advantage in an A2/AD environment, the proposed ALC is a real alternative to the connectors that are currently in use. The only issue that the capstone team ran into was that a significant amount of work required to develop the performance parameters for a conceptual design, specifically defining the size, weight, speed, and horsepower for a given hull design. After evaluation of several hull designs, research suggested the catamaran style hull would be a great fit, but speed power curves were required for a proposed electric motor if the model was going to effectively simulate the ALC's performance.

The capstone team did reach out to several naval architects who currently teach at the Naval Postgraduate School (NPS) with the help of the capstone advisors, but the level of effort for the conceptual design, with all the other undertakings, was too great to complete in the nine-month capstone project timeframe. For this reason, a third connector the LCAT was identified because of its hull style and operational capabilities that are similar to what was envisioned for the ALC. It was believed that the modeling and simulation of this platform would provide insight into whether a platform with these types of design parameters would be effective in an operational scenario. Not only was the LCAT effective, but it was one of the key reasons three scenarios met mission effectiveness for all combinations of SSD and SS. The results of this capstone project

show that an LCU-like design, with performance parameters similar to the LCAT, should be further pursued. While traditional diesel engines can be configured for some level of energy efficiency, the capabilities of current electric motor technology seem to suggest that the use of alternative energies for a seabase-to-shore connector is feasible. While the use of batteries to power a connector has its challenges, tactical advantages such as silent operation could be critical to operations in an A2/AD environment. It is hoped that an ALC-like platform could be further evaluated in a future capstone project, to define the power plant and hull properties needed to develop the speed power curves to simulate an alternative energy platform.

The following report, “Seabase to Shore Connector Analysis of Alternatives” completed in November of 2007, was identified during this capstone project’s conceptual design research. It was very helpful in presenting alternatives to replace the LCAC, but the report did not provide any of the performance information with which to develop the factor inputs to the M&S, with the main missing parameter being a fuel burn rate. It is believed that further evaluating this report and working to obtain some of the supporting information behind it would prove helpful if another capstone team were to undertake the challenge of an ALC conceptual design.

5. Addition of Battle Damage to Models and Simulations

The E2O stakeholders expressed an interest in battle damage assessment (BDA) and how damaged surface connectors would impact the STOM mission. The NPS capstone advisors identified a cellular automaton model named Map Aware Non-uniform Automation (MANA) that could be used for BDA scenarios. BDA scenarios were considered during the capstone proposal phase; these scenarios were based on damage from A2/AD events impacting STOM performance by decreasing availability of damaged connectors. The capstone team did not have any experience with BDA scenarios, MANA, nor did it obtain specific guidance that enabled this modeling effort; so, an assumption was made to exclude this effort and limit the scope of this study. Additionally, BDA scenarios would have provided an uncontrollable scenario from which to adequately evaluate fuel consumption. This capstone project was focused on determining the most

energy efficient way to obtain operational effectiveness that could not have been achieved with simulated battle damage impeding a level playing field for all connector scenarios.

6. Air Combat Element Integration

One of the most impactful assumptions with respect to fuel usage made during this capstone project was that energy consumption for air combat element (ACE) operations would not be within the scope of this project. Though this capstone project did require combat air patrol (CAP) and close air support (CAS) in response to a call for fire (CFF), the model did not calculate the additional energy consumed by ACE assets that supported the surface connectors during the STOM mission. Under consideration for the ACE were the AH-1Z Cobra, AV-8 Harrier, and F-35B Lightning II aircraft that were deployed to provide air cover and strike support in response to A2/AD events involving SAF. The time and expertise required to explore the integration of the ACE in support of our STOM mission was not within this capstone team’s abilities.

The capstone team considered the use of air lift connectors to transfer portions of the MEU elements vice transferring the portions via surface connectors; however, the team lacked specific knowledge of these aircraft and decided that integrating air lift platforms into the STOM would exceed the available scope of the capstone project. This capability should be added to the baseline model to better assimilate with real world STOM operations. Once the air lift connectors are defined in the model, logic must be added to control the selection of connector type when considering payload weight and displacement, priority and timeliness, and energy savings. The MV-22 Osprey and CH-53 Super Stallion are both recommended air connectors for this future expansion.

C. CONCLUSIONS

This study used Model Based System Engineering (MBSE) and modeling and simulation (M&S) to look at the tradeoff effects on various combinations of surface born connectors specifically on the mission effectiveness factors of fuel consumption and time-to-complete the seabase-to-shore portion of a notional STOM. A focused physical architecture was established for a subset of the ship to shore maneuver that allowed for

the effects of each function to be studied. In addition, the controlled set of environmental, tactical, and connector characteristics were studied in detail. The analysis conducted yielded four primary conclusions.

Conclusion one: The mission objectives for throughput and fuel consumption could not be met in all scenarios by varying the combination of LCU and the LCAC alone.

The LCU and LCAC constitute the primary existing Marine Corps heavy-lift cargo connectors employed in seabase-to-shore off-loading operations presently. These two craft contrast significantly in their basic characteristics pertaining to speed and fuel consumption, as well as in the operational and environmental factors that affect the performance of each craft. The LCAC's substantial advantage in speed contributes to reduced mission package transfer times under many conditions. The craft's fuel consumption, reduced payload, and deteriorated performance in higher sea states, however, reduce its effectiveness in many operational scenarios and require that it be paired with higher number of LCU to offset these deficits. In contrast, the LCU has greater lift capacity and fuel efficiency but is less effective in contributing to the objectives for mission package transfer times. By analyzing all the possible combinations of the two craft supported by the three-ship ARG, and exercising those combinations across each defined environmental and operational scenario, it was possible to identify multiple scenarios where the mission objectives could not be met by various combinations of the existing cargo connectors alone. This finding suggests that the characteristics of the LCAC and LCU are sufficiently contrasting that a capability gap exists across some potential scenarios of operation. This finding supports the motivation to analyze an alternative connector craft.

Conclusion two: The introduction of an alternative intermediate-capability connector provided solution sets meeting all mission objectives.

At least two options exist to address the capability gap suggested by the analysis of LCAC and LCU operation alone; the characteristics of the LCAC and LCU could be modified in an attempt to create a solution space meeting mission objectives in more

scenarios, or an alternative craft with intermediate capabilities could be introduced to assess the effect on the solution sets. The statistical analysis summary in Appendix H indicates that the AS for the maneuver did not meet operation effectiveness for most scenarios that had three or more LCU, even if they did meet Mission Package Transfer Time and Total Fuel Used requirements. This suggests that the transit speed of the LCU may be insufficient to meet mission effectiveness. In contrast, the response surface profile favors higher numbers of LCAC to maximize the desirability of the solution set. Both these findings point to the importance speed plays in meeting mission effectiveness, and the challenges of that exist in increasing the solution sets by modifying the two existing craft. The high block coefficient resistance characteristics of the LCU hull-form make it impractical to increase the speed substantially, as would be required to affect overall the AS of the connector pair. The powering requirements and main machinery of the LCAC offer little opportunity to improve fuel consumption at full load while on-cushion. These factors support the introduction of an alternative craft design as a means to increase the solution set. Additionally, the availability of design data for a viable alternative craft influenced the decision to pursue this latter option. The LCAT prototype had the mature design data required to meaningfully represent it in the physical architecture of the model, operational and functional characteristics that were compatible with all aspects of the scenario, and the demonstrated operational history to support it as feasible option. With performance characteristics representing an intermediate capability between the LCAC and LCU for both speed and fuel consumption, it was selected as a viable candidate to introduce as an alternative capability in the analysis. While the LCAT itself may in fact be a feasible alternative, the desired outcome in the analysis was to demonstrate the effect on the solution sets from the introduction of a notional craft with intermediate capabilities.

Three connector combinations out of the possible set of 27 were capable of completing the ship-to-shore maneuver within all mission effectiveness criteria across all factor inputs. Each of these solution sets contained at least four LCAT. This finding suggests that there is the potential for an alternative connector with intermediate

capabilities to improve the mission effectiveness of the ship-to-shore maneuver. The results can be found in Appendix I

Conclusion three: Alternative energy technologies, in combination with diesel-electric generators, can contribute to reducing the fuel consumption of MAGTF command element operations ashore.

The viability and capacity of renewable energy technology for electrical power generation is evolving rapidly. This evolution, fueled largely by investments in the commercial power generation sector, is motivated by the desire to increase the sources of supply, improve flexibility, and reduce the fossil fuel consumption of the terrestrial power grid. These motivations have close parallels to the tactical needs of the MAGTF for conducting command and control operations ashore. While diesel generators are likely to constitute the majority of the energy produced to support MAGTF CE operations for some time to come, the analysis conducted in this capstone project provides an assessment of some viable alternatives with the potential to supplement this capability in the near term.

Strategies, such as FlexGen, that incorporate demand management, storage, and the ability to accept generation from alternative sources, provide the immediate potential to improve efficiency within the existing power generation architecture. Renewable source technologies continue to evolve rapidly in their capacity and power density, and are being integrated into the commercial grid at an increasing rate. The analysis indicates that power-dense deployable wind generation options exist today which could be made compatible with expeditionary operation and contribute to the fossil fuel reduction goals. Solar looks to be the next most viable option but does not yet have the power density to package the necessary capacity into a module suitable for expeditionary deployment. Both these technologies, however, appear to be at sufficient maturity to be considered for smaller scale integration into existing architecture to assess their expeditionary suitability.

D. RECOMMENDATIONS

The major conclusions drawn from the MBSE analysis conducted in this capstone project point to the concept that a potential alternative intermediate-capability craft, such as the LCAT, may be critical in improving the energy utilization of the surface connector fleet while maintaining or improving mission effectiveness. The access to operational data generated over multiple years of testing and joint exercises with the LCAT prototype provides an opportunity to improve the fidelity of the baseline model craft in this effort for further analysis. Over the past 10–15 years, the Navy has been searching for the next generation connector to comply with capability gaps and phase out end-of-life platforms. Though numerous analysis-of-alternatives have been conducted in an attempt to provide direction to the acquisition agencies, the research performed the capstone team found no alternatives similar to the LCAT. With operational data readily available, it is recommended that the LCAT be evaluated against other connectors in an analysis-of-alternatives to determine whether it has the potential to be seriously considered as a replacement.

Additionally, the capstone project has shown the potential for alternative fuel technologies to subsidize diesel-based power generation to the levels sought after by USMC doctrine. Current E2O programs-of-record (POR) seem to be entirely based on solar power. It is recommended that the E2O further explore the use of hybrid energy storage based solutions like FlexGen or wind based solutions like the portable wind turbine developed by Uprise Energy as potential PORs to meet the growing power demand by alternative energy solutions in the battlefield.

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APPENDIX A. SYSTEMS ENGINEERING PROCESS

Systems Engineering (SE) in the Department of Defense (DOD) has been in practice for many years and was mandated in April 2002 with the release of the original DOD 5000.2 instruction "Operation of the Defense Acquisition System" (2002, 2). The instruction has since been superseded several times by DOD 5000.02 of the same title, whose latest release was January 7, 2015. The DOD SE process is a characterized by exhaustively replicated actions performed at ever increasing levels of detail, and applied successively in a top-down or bottom-up manner by integrated product teams (IPTs) resulting in the transformation of stakeholder needs and requirements into products and systems. This process or collection of processes has been studied and refined since the inception of SE and is tailored to the needs of the program or project the process shall be used on. The main steps of the process, as applied to this capstone project, are discussed within this chapter with further details delineated in subsequent chapters.

This project began by identifying the problem and validating the stakeholders' vision of the problem, defining the system, and refining the system according to quantitative and qualitative measures. The process begins with the problem statement. This problem is then decomposed into the concept of operations. Because this capstone project is relying on modeling and simulation, an extra emphasis was placed on deriving appropriate measures for use in the analysis. Measures of performance (MOPs) and measures of effectiveness (MOEs) were derived during the requirements analysis described in Chapter 2.

The project continued from the definition of the measures to establishing simulation models, running a design of experiments upon those models, and drawing conclusions from the results. Functional analysis and allocation aided the production of the models by comparing the functions to the measures defined earlier, as well as any test cases that were specifically simulated to evaluate the MOEs/MOPs. Design synthesis is an iterative process that incorporates different approaches to solve a problem and was used to create all of the parameters of the model. The inputs, constants, and equations used in the model all have major effects on the simulation outputs seen within the model.

Models were created and executed for thousands of runs. The design of experiments (DOE) was used to determine what variables and factors were significant. The significant factors were then further evaluated and rerun through the model(s) to determine their total effect. By determining these significant factors and their effects, the stakeholders are shown which of their decisions make the greatest impact on their objectives. The capstone team then analyzed these effects, the results of the effort were determined, and conclusions were established. The project concluded when the DOE results and M&S outputs were compared against the original problem statement and the requirements, and their impacts were verified and validated.

A. PROBLEM

Defining and validating the problem was a vital function performed early in the project. Defining a problem can itself be problematic, but it is a singularly critical activity to project success. This capstone project started with several examples of well-defined problems from previous capstone projects, helping to build a clear understanding of the problem early in the life cycle. The common context for this and the previous capstone projects was the analysis of operational and energy effectiveness in the execution of sea-based expeditionary maneuvers. Based on the results and recommendations of these previous capstone projects, as well as guidance from the E2O Sponsor, the problem statement for this capstone project effort was established:

> The United States Marine Corps must transport troops, vehicles, supplies, and logistics support from a seabase to a shore site in a rapid and orderly fashion. They must then support these personnel and equipment by establishing a supply line that delivers all perishable and depletable resources to the force by land, sea, and air. The mission is effective when the transport of troops, platforms, supplies, and logistic support from seabase-to-shore is accomplished with minimal loss of life. The purpose of this capstone project is to increase the energy efficiency of the operations while maintaining this operational/mission effectiveness.

1. Define the Problem

The problem definition was conducted in five steps: stakeholder analysis, literature review, definition of the system boundary, decomposition of the requirements,

and construction of a context diagram. After conducting these steps, the problem to propose to the capstone advisors was agreed upon after analyzing the findings.

The capstone team defined the system inputs, which included the customers' needs, objectives, requirements, and constraints. These inputs were received as guidance in the initial capstone stakeholder meeting from the stakeholders directly as well as from a literature review of available E2O documentation and official E2O published guidance. The combination of the stakeholder input and literature review were used to identify the initial architecture, the problem background, and the context of the stakeholders' views. This literature review allowed this capstone project to determine how the problem had been approached in the past, and whether any past results could be leveraged in the current efforts.

This capstone project began scoping the problem by defining the system boundary. Scoping the problem ensured the resultant effects were achievable in both the schedule and technical capabilities. Once scoped, the problem statement, stakeholder analysis results, and literature review were compiled into requirements. The requirements were analyzed and decomposed into functional and performance requirements, while ensuring the requirements were understandable, comprehensive, complete, and concise. Lastly, this capstone project constructed a system context diagram to understand how the system interacted with its environment and how it was intended to be used. The context diagram was also used as the first step in validating the problem.

2. Validate the Problem

Continued through the model the functional analysis and allocation determined what functions were required within the problem context and how these functions were notionally applied to solve the problem. The functions were analyzed to better understand the system purpose. Outputs included functional flow block diagrams, timeline analysis, and the requirements allocation. The feedback loop from the functional analysis to the requirements analysis verified that the finer requirements were traceable to the original requirements.

Problem verification and validation involved the use of the Marine air-ground task force (MAGTF) Power and Energy Model (MPEM) whenever possible. When data, formulas, or process was not available in the MPEM, we used a defensible methodology including assumptions, formulas, and process flow from sound SE estimation. The methodology is limited in some areas due to lacking information so assumptions were used to prevent project delays. Methodology was described and discussed in detail with the NPS advisors and E2O sponsors and concurrence was received. The model accurately represents the STOM mission within the scope of the project as defined by the conceptual description and specifications provided by stakeholders (DOD 2009, 2).

Several methods of problem validation were used to assess and improve the degree of accuracy demonstrated by the M&S effort. Predictive validation (Law 2007) was used in most cases; however, existing model comparisons, such as MPEM and sea state, were also used. Performance characteristics from face validity such as consults with a previous USNR/LCAC Craftmaster and subject matter experts (SMEs) were also used. Parameter variability was used by changing the model input values and determining the effects on model output. The model output responses were compared to the responses expected from a virtual system created from face validity (Law 2007, 257–264).

Random variability in simulation events was used to create a stochastic system. Each random variable was validated independently to ensure it stayed within the design limits determined. The stochastic elements were disabled within the model to increase predictability and validate the model responses before re-enabling for final design of experiments (DOE). The modeling and simulation scenarios resulted in a stochastic system that explored the STOM trade space with random variability over a total of 52,650 simulation iterations. The random events provided a broader range of exploration leading to results that are statistically closer to STOM mission performance thus increasing the degree of accuracy of some simulation runs. Slight variations in surface connector speeds (normally distributed +/- 10%) and the A2/AD RPG launching event throughout the STOM with a 2% probability of an RPG launch each time a surface connector is within range.

B. SYSTEM DEFINITION

The second major process of this capstone project's SE approach was the system definition. System definition allowed for the exploration of the trade space and any alternatives present for the system. The system definition was first explored through the Concept of Operation (CONOPS) and by developing the scenario, assumptions, and constraints of the system within the context of its mission. As the CONOPS became better defined it was refined according to the specific scenario chosen and the simplifying assumptions necessary to derive significant results. There are two parts of the system definition—the system boundary and context diagrams—used as the basis for the CONOPS (Chapter III) and the system architecture (Chapter IV)

1. Concept of Operation/Scenario Development

Evaluation of stakeholders' objectives, analysis of mission requirements, functional analysis and allocation, and design synthesis were all techniques used to develop the concept of operations and mission objectives. These techniques included the research done in the problem definition and problem validation steps which allowed this capstone project to select and tailor a CONOPS that would fit the needs of the stakeholders as well as the capstone team. This section outlines the high level CONOPS laid out for this capstone prior to the simplifying assumptions made.

Marine Forces Pacific (MARFORPAC) or Marine Forces Atlantic (MARFORLANT), generically Marine Forces Command (MARFORCOM), establish a seabase location and deploy a MAGTF sized according to the mission. The MAGTF maintains readiness by operating the command element (CE) from the seabase while coordinating daily drills as they prepare for a ship-to-objective maneuver (STOM). MARFORCOM planners modify existing operational plans (OPLANS) based upon the availability and capability of sea and air lift connectors; sea, ground and air attack platforms; time to close from seabase and surrounding locations; and fuel consumption from the shore base.

The STOM is executed in two phases in accordance with a STOM notice. The CE, ground combat element (GCE), logistics combat element (LCE), and aviation combat

element (ACE) are deployed to shore in accordance with phase I of the STOM notice. The second phase of the STOM notice forward deploys the GCE from the CE site to the adversary objective site. The first portion of the MAGTF to go ashore is the GCE, which will establish a secure perimeter inland for the CE. The remaining CE followed by the LCE and a mission appropriate portion of the ACE will relocate from the seabase to the secure perimeter upon GCE notification,

The MAGTF commences STOM planning immediately following receipt of the notice from a MARFORCOM. Surface connectors are obligated and readied for equipment and personnel uploading. Air lift connectors are placed on ready standby to deliver the GCE equipment and personnel as needed. Attack aircraft are placed on ready standby to provide close air support (CAS) and combat air patrol (CAP) as needed.

The MAGTF LZ, the secure perimeter for the CE and the GCE movement to the shore site are all within the area of operation for the situation. Small UAVs are used to provide aerial intelligence, surveillance, and reconnaissance (ISR), detect, and locate adversary activity, in conjunction with ACE elements from the seabase on ready standby for CAP and CAS sorties. If adversary A2/AD activity increases during the STOM, aircraft will be launched to provide aerial combat cover and protect the force while the sea lift connectors are operating. The A2/AD tactics employed increase fuel consumption if aviation assets are required to protect or air lift the MAGTF forces.

Figure 40 shows the OV-1 for the STOM of the MAGTF GCE, CE. and LCE. The CE operating aboard the seabase controls the transfer of personnel and equipment starting with the GCE to establish a secure perimeter for the remainder of the MAGTF. The CE on the seabase continues to control and monitor transfer activities while the ground based CE and LCE personnel and equipment are detached, uploaded and transferred to shore under the control of the CE operating on the seabase.

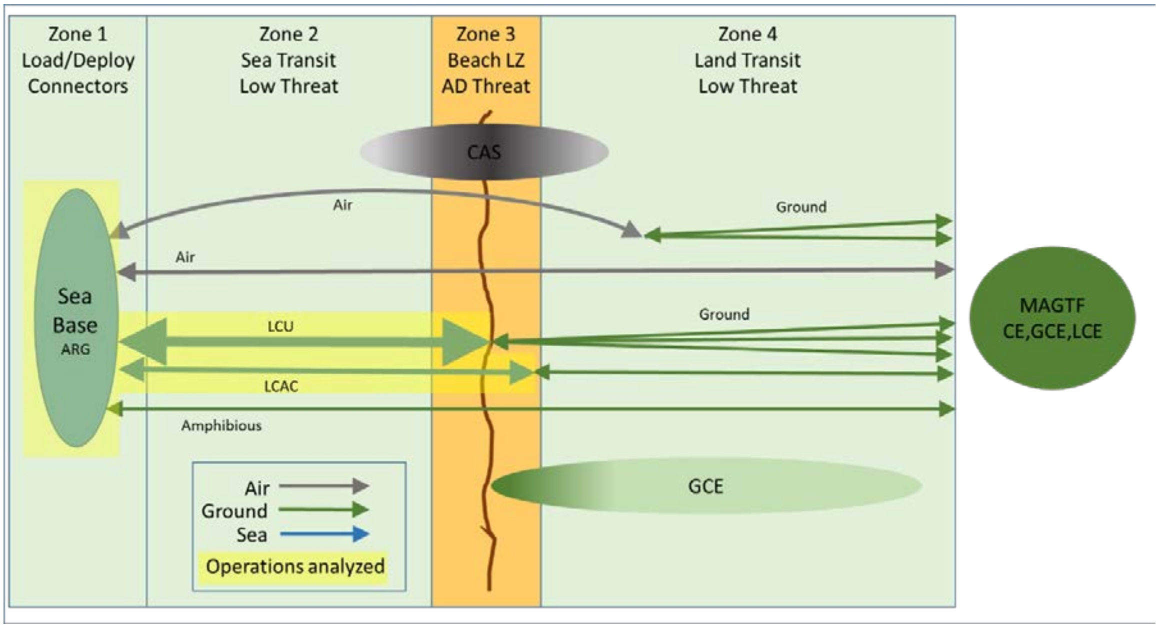

Figure 40. STOM OV-1

2. System Architecture

The System Architecture was tailored for the scenario used in this capstone project. Since the capstone project involved many events, the architecture was developed in a way to allow the study of each event. To satisfy the capstone project requirements, each function in the architecture was validated and traced to the main requirements. The architecture was constructed in Vitech CORE to allow management of each function. In addition, this software provided traceability to functions and components from the requirements.

After understanding the scenario being studied, the capstone team engaged in further reading to research the appropriate units needed for simulation. The units consist of MEU personnel, amphibious vehicles, and enemy threats. The architecture was crafted from the functions needed for the E2O mission. The E2O mission consisted of a seabase-to-shore operation and a sustainment portion at shore. These operations were split into two because they utilized the MAGTF units in different fashions. The seabase-to-shore operation required the use of connectors to transport the MEU and supporting equipment to shore. In addition, the ability to counter A2/AD was needed to properly conduct a

simulation study. Renewable energy sources were researched to lower the fossil fuel footprint while the MEU was at shore.

As the capstone team broke down the scenario into partitions, it allowed the architecture to be developed in a way that enabled different simulation tools to be used. A functional architecture was derived from the scenario, which supports the simulation efforts. The partitioning of the scenario provided a better understanding on how the functions of each physical component performed. In addition, the complexity in creating the architecture was reduced since partitioning separated the functions that did not apply to both.

C. MODELING AND SIMULATION

The models and simulations for the capstone project were partitioned into two portions. This included the seabase-to-shore and the sustainment effort. Partitioning these efforts allowed the team to utilize different simulations tools for each scenario. The seabase-to-shore portion was simulated using ExtendSim and analyzed with JMP Pro. The sustainment portion was simulated using the supplied MPEM. The design flow and functions will be discussed in this section for each model.

The modeling and simulation tools explored mission inputs to determine operational effectiveness. Outputs of the modeling and simulation effort determined whether energy efficiency could be improved through both materiel and non-materiel means. This study provided data in support of reasonable solutions used to assess fuel consumptions while maintaining mission.

In the design synthesis step, a solution was proposed, a physical architecture was defined, and the basic structure for generating specifications and baselines was created. The design loop, similarly to the requirements loop, verified that the functions were performed within the physical design.

1. Models

The capstone team used a model, or a conceptual simplification of the system, in order to produce factual information about the desired behavior of the surface connectors

(Blanchard and Fabrycky, 170). This model was the basis for a discrete event simulation used to conduct a statistical analysis of the craft behavior in varying operational scenarios.

The first step in this analysis was to bound the problem and establish a simplifying set of assumptions that allowed for the complex real-word behavior of the craft to be conceptualized in a manner, effectively answering the capstone project's research questions. The boundary conditions for the analysis were established to represent the high-level interactions governing the movement and the operation of the individual landing craft between the seabase and the designated landing area.

A discrete event simulation was used to evaluate the model numerically in order to generate data to statistically estimate the true characteristics of the model (Law 2007, 1). The simulation was developed to explore the essential relationships of these elements. Once the problem space had been conceptualized, the simulation was divided into the principal elements governing the craft behavior. This simulation was used to identify the critical logical relationships of the elements within the system and their principal effects on the behaviors of interest. These logical relationships were used to then derive a mathematical model within the simulation. The mathematical model represented the system elements and their interactions.

The initial step of conceptualizing the problem was to identify the elements of the scenario, and, within the established boundary conditions. determine the scope of operations that were covered by each assumption. The resultant conceptualized scenario focused on reliably answering the research questions proposed in Chapter I.B (Buede 2009, 75).

The schematic model represents the state of the formal relationships that exist between the various elements of the system. This model established the time-varying interaction of the elements over a complete cycle of the ship-to-shore operation (Blanchard and Fabrycky, 174). The simulation divided the ship-to-shore cycle into three sequentially related phases; Initialize Run and Pre-Load, Transit and Offload, and Return

and Re-Load. These phases were used to assemble the individual elements of the ship-to-shore cycle into groups of common functions with dependent relationships.

The elements in the Initialize Run and Pre-Load group are executed prior to the start of the timed portion of the simulation. They establish the starting condition for the cycle and define the fixed factors that are present throughout the duration of the run. The transit phase of the simulation defined the simulated movement of the individual craft between the seabase and the designated landing areas. In this phase, logic was established that governed individual craft movement and the interactive effects of the environmental and threat factors on the craft movement. Upon return to the seabase the craft entered into the reload portion of the simulation. Here the logic that determined the load-out and sequence of the mission package contents were established, as well as the logic controlling how the mission package was loaded onto the individual craft. This portion of the simulation also established the relationships used to determined that the conditions for mission completion have been met.

With the logic relationships established, the system was then represented in terms of logical and quantitative relationships that were manipulated and changed to see how the model reacted. This was done by numerically exercising the model's input factors, found in Table 4, to assess how the output measures of performance were affected (Law 2007, 5).

2. Verification and Validation

The conceptual model was built using data, process references, and information from the MPEM, MCTL, sea state table, alternative surface connector and alternative energy research, guidance determined during IPRs, and several references from the Marine Corps website (USMC 2014; USMC 2016; MCRP 3–31.1A 1997, 8–8). With the exception of data and information from research, the remaining sources were assumed to be authentic and informally verified as accurately defining a STOM mission. The capstone team's follow on discussions with a retired LCAC Craftmaster and E2O leadership further verified and validated the conceptual architecture and model. The conceptual model architecture, process flow, input factors, and results were presented

during IPRs and documented in the capstone project proposal. The conceptual model was discussed and verbally verified for accuracy.

The conceptual model, as a guide, drove the development of an ExtendSim STOM model where formal steps were taken to verify and validate the model. The capstone team verified the STOM model by comparing it to the conceptual model with the objective of producing an accurate and credible model. All input factors were verified by mathematically predicting results before the model was run. Randomization built into the model was removed to increase predictability of results during model verification and then added back into the model once verification was complete. A few static test scenarios were configured to drive the simulations and confirm the results were accurate using two database tables. The Outputs table showed the final results of each simulation run and the STOM table stored detailed status records for each surface connector as the STOM progressed.

The STOM model was verified and validated to the degree needed for the model to simulate a STOM mission. Input parameters, called factors, were isolated and verified independently during sensitivity analysis to determine their range of variability and effect on STOM processing and results. The STOM model was tested during verification and all discovered errors were corrected. Some errors resulted in corrections to the STOM model where others resulted in slight editorial changes to the conceptual model. Expert confirmation and logic flow diagrams were used to verify the STOM model was properly sequenced and mission processing was implemented enough to complete the capture of needed data. Model outputs were examined to verify reasonableness and that they matched expected values.

Verification was conducted from the solution to the original requirements to ensure all requirements were satisfied. Each requirement was verified at each level of model development with all technical decisions and all specification requirements related to the overall SE outputs. Verification included inspection, demonstration, and testing of each element. In addition, formal test and evaluation became important contributors to the verification of the system. The capstone team performed the verification of the

requirements while maintaining traceability from the inputs to the outputs of the SE process.

3. Design of Experiments

This capstone project used the design of experiments (DOE) methodology as a comprehensive and efficient way to develop a design matrix from which simulation runs were performed to obtain as much information as possible for the seabase-to-shore operational scenario. Selection of the DOE design type was critical in determining the combinations of factors required to properly evaluate the scenario without having an infeasible amount of simulation runs. In general, the DOE provides a structured approach to varying the simulation input parameters that ensures that the assumptions of follow on statistical analysis are not violated. A space filling design that minimized correlation between the input factors and maximized the coverage of the design space was used to populate the DOE matrix. These factors were then used as inputs for the seabase-to-shore operational model to get a numerical result for each response during the simulation runs. When the simulation runs were completed using this design matrix, the response data was transferred from the model to a statistical software called JMP Pro to perform a detailed statistical analysis of all factors to each response. The specific details about the DOE methodology that was selected by the capstone team are discussed in Chapter IV.

4. Simulations

The simulations for this capstone project used 14 input factors that were configured in 65 distinct combinations. These factor combinations, when applied to 27 distinct scenarios bounded by a three-ship ARG, were replicated 30 times to account for the stochastic nature of the simulation study, and to produce a total simulation run count of 52,650. The simulation run count allowed for full exploration of factor variability using a feasible amount of simulation runs. The simulation results provided an ample amount of data to properly evaluate the scenarios using JMP Pro for detailed statistical analysis.

The model implemented stochastic properties to add unpredictable behavior that better explored the replicated scenarios. A normal distribution was used to randomly vary

craft speeds by +/-10%. The A2/AD RPG event randomly resulted in a launch probability of 2%. This stochastic behavior changed craft loiter times causing random changes in fuel consumption. Several samples of the 27-scenario set were run, tested and verified before attempting to run the complete design to properly evaluate all scenarios with full range of variability. The results from each of the 52,650 simulations were captured and used for statistical analysis.

5. Statistical Analysis

This capstone project conducted a statistical analysis to investigate the results that were obtained for each response of the seabase-to-shore operational model. Specifically, the purpose of the statistical analysis was to identify and investigate the factors that have the most significant effect on each response of the seabase-to-shore operational scenario. As mentioned before, this capstone project used a statistical software called JMP Pro to conduct the statistical analysis for each response of the seabase-to-shore operational model. Additionally, this capstone project used JMP Pro to identify the feasible solution space during the trade space analysis that was performed as part of the statistical analysis. This solution space provided the data necessary to draw conclusions on key design parameters, the best combination of factors to satisfy MOEs, and alternatives to present to the stakeholder. The specific details of how the capstone team conducted the statistical analysis are discussed in Chapter IV.

D. RESULTS AND CONCLUSIONS

The results and conclusions were strongly tied to the statistical analysis of the modeling and simulation efforts. This analysis was done using statistical analysis software that provides the tools to create a statistical metamodel. This metamodel was used to relate this capstone project’s input factors to the output responses. Evaluation of these parameters determined what factors were significant to the MOEs and what combination of parameters performed well within the solution space. Use of the metamodel allowed for estimation of system behavior and the development of the observations that conclusions were drawn from. These observations were then used to develop answers to the research questions identified in Chapter I. The systems

engineering process provided the methodology to obtain these conclusions for the complex behavior modeled and identified the solutions needed to meet stakeholder requirements.

1. Results

There were two main sets of results for this capstone project, one from the modeling and simulation runs and the second from the statistical analysis. The modeling and simulation runs produced 52,650 data points based on the DOE that captured the interactions between the factors and responses. While some insight can be gained by viewing one data point at a time, this technique did not provide a broad evaluation of all the data sets as a whole. The capstone team's use of the statistical analysis software allowed for the exploration of these interactions and identified which parameters were significant. To do this, the statistical analysis software creates a metamodel which is a mathematical representation that relates the factors to the responses. It is from this metamodel that statistical analysis results can be viewed in numerous analysis plots and graphs, with some graphs providing real time analysis through manipulation of the factors to determine the trade space. It is this trade space visualization that provided the means to evaluate combinations of factors to the responses and present the results in such a way that conclusions can be drawn.

Additionally, at this point in the capstone project the results were verified and validated against the requirements. That is, the results were analyzed to determine whether they made logical sense. With any modeling and simulation effort of this size, the model needed to determine whether the data acquired and the data compiled were in agreement with the concept of operations, design parameters, performance parameters, and general assumptions and constraints that originally defined the model. Once the statistical analysis results were validated, conclusions were drawn to identify which parameters were significant to stakeholder requirements. From this significance, design parameters are explored to determine what combination of factors fall within the solution space. Typically, alternatives are presented to the stakeholder to identify a way forward with consideration for system effectiveness, performance, cost, and value. For this

capstone project, several alternatives were identified from the solution space resulting in several different conclusions.

2. Conclusions

The final step in the systems engineering process is to draw conclusions from the results and present alternatives to the stakeholders. Using the statistical analysis software, the results of the modeling and simulation were analyzed using the following plots: analysis of variance (ANOVA), normal, pareto, prediction profiler, and contour. The ANOVA plot identified whether the regression model was a good fit for the entire data set. Additional tables helped to support this determination including: the "summary of fit," "effect summary," and the "actual by predicted" plots. For the ANOVA, if the p-value was low, it meant the model was a good fit and the results could be used to provide an accurate estimate of system behavior.

Once the model was determined to be a good fit, the normal and pareto plots were used to determine the significance of factors. Furth, those plots prioritized the input factors in terms of the impact that they had on responses. The most impactful factors were the ones that were further explored with the prediction profiler and contour plots. The prediction profiler allowed for the comparison of all the factors against each response to determine the interaction between variables. The factors with the largest slope had the most effect on an output variable. There was also a function that allowed the user to maximize desirability. This function returned the optimized value of each factor for a provided set of desirability with respect to the response. These values were then utilized in the contour plot to show the design space. Limits were applied for each response to find the solution space for a given set of responses. Since the responses were derived from the MOEs, the solution space contained values for the factors that were attributed to the parameter values or measures of performance (MOP) that were required to meet operational effectiveness.

For this capstone project and the seabase-to-shore effort, the above approach was taken to identify significant factors that had the greatest impact on the overall mission. Additionally, the connectors were evaluated to determine which performance parameters

had the greatest effect on the responses and the best combination of connectors to meet mission effectiveness. These determinations also framed the answers to the research questions identified in Chapter I, Section B.

For the sustainment operations, MPEM was used to evaluate electrical power generated from the top three alternative energies that were obtained from a quantitative analysis. The electrical power numbers were then compared to the current year's renewable energy goals to determine the number of systems required to meet this demand for each alternative energy. These values were then used to answer the research question identified in Chapter I.B.

With these conclusions in hand, alternatives were identified to meet the goals and objectives provided by the stakeholders. For the seabase-to-shore effort, combinations of connectors that met operational effectiveness while reducing total fuel consumption were obtained. Additionally, insight was ascertained for what performance parameters were most significant to overall mission success. For the sustainment operation, potential alternative energy solutions were provided to meet renewable energy goals, with the overall mission to reduce total fuel consumed for the shore site power demand. The results, conclusions, and alternatives are supported with details on total performance, cost, life cycle costs, risk, and value for presentation to the stakeholder. For both efforts, the modeling and simulation tools were made available to further analyze the given scenarios, or expand the analysis for new capabilities and parameters should the need exist. This systems engineering process can be iteratively repeated as necessary to define new solutions to ever-changing mission parameters.

APPENDIX B. ARCHITECTURE DIAGRAMS

An expansion view of how the architecture was modeled in Vitech CORE can be found in these sections. In order to understand the flow in which the simulation effort would take place, ExtendSim was used to model what functions were needed to be included in the simulation. These functions and relations were derived though the use of Vitech CORE. The common context for this and the previous capstone projects was the analysis of operational and energy effectiveness in the execution of sea-based expeditionary maneuvers. The team, through understanding the problem statement, developed a functional architecture to capture the overall functions the MEU performs during its missions. After creating the overall hierarchy these functions were decomposed. Through this decomposition, relationships between elements, inputs, and outputs were added to the architecture. The software tool called Vitech CORE organized and managed this architecture. In the CORE software nomenclature, functions are titled with the letter "A" and components are titled with the letter "C," similar to IDEF0. In this chapter, the system architectures represent the hierarchical functions, the specific components that perform those functions, and the relationships between the two. The relationships between the components and functions can be seen in the EFFBDs; however, due to the embedded software rules, only one relationship can be assigned per function. The names of the components are used to create the relationship to the functions and can be found under each function block.

A. SYSTEM FUNCTIONAL ARCHITECTURE

In order to relate the idealized behavior modeled in the simulation to actual mission functions, a hierarchical structure was created to capture both efforts. As shown in Figure 41, the two top-level functions for the model were "Perform USMC Expeditionary Operations" and "Perform USMC Expeditionary Simulations." The USMC simulations emulate the functions performed by the USMC operations. The functional model was created this way due to the operations and simulations being very closely related, the main difference being the simulation section also captures the

activities relating to M&S functions. This architecture was used to define the sequence of events modeled in the simulation analysis. The process of creating the "Perform USMC Expeditionary Operations" functions helped identify any missing functions in the model and became a guide to complete the simulation functions.

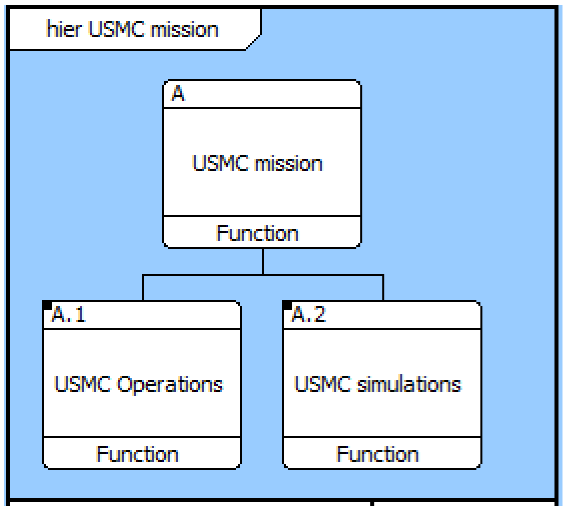

Figure 41. Top Level USMC Mission and M&S

1. Hierarchical Breakdown

The first function "Perform USMC Expeditionary Operations" was decomposed into the discrete functions shown Figure 42. The capstone team used these functions to establish the process flow for performing the operations; which, in-turn, were used to create the simulation for analysis. For this capstone project, only the first two elements were explored; "Transfer from seabase to shore" and "Provide shore site energy logistics." The function "Transfer from seabase to shore" describes the primary top-level function analyzed, and captures the sub-functions required to transfer the MEU from the seabase to the shore in order to complete the mission. Through the process of transfer, everything that is needed by the MEU is transported. The function also accounts for any threats encountered during transfer. The function "Provide shore site energy logistics" captures the fuel burn rate and energy demand of the MEU while operating ashore. The breakdown of this function provided an understanding of how renewable energy can be

used to support the MEU. The functions not studied, shown in red in Figure 42, require more time to complete and are identified as candidates for future study.

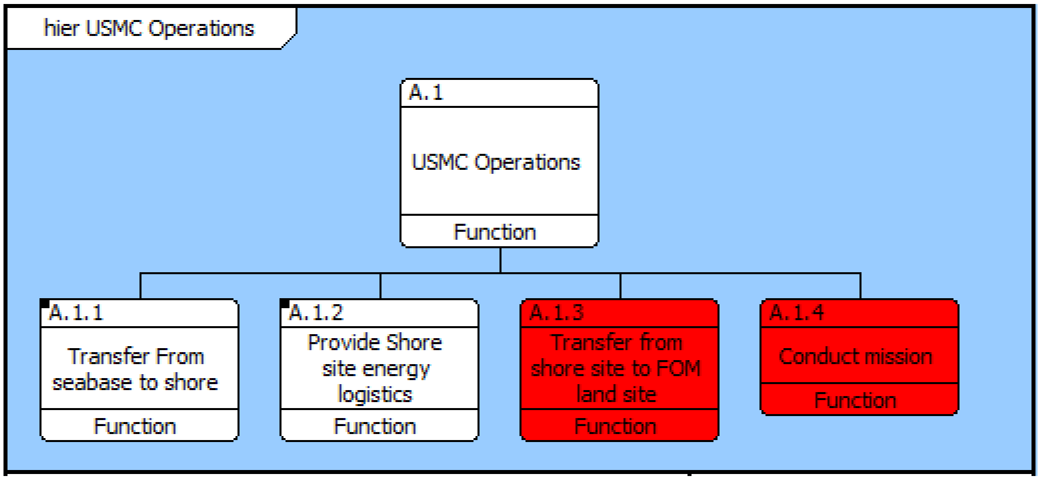

Figure 42. Hierarchical Function Structure of Perform USMC Expeditionary Operations

The functions A.1.1 and A.1.2 can be furthered decomposed into sub-functions as shown in Figure 43 and Figure 44. A.1.1 was decomposed into four elements, while A.1.2 was only decomposed into three. The function "transfer from seabase to shore" has many sub-functions that needed to be simulated to ensure the study is done correctly. Understanding that personnel and equipment needed to be transferred while countering A2/AD was required. Figure 43 shows these functions captured in a hierarchical method and are further broken down in the CORE models. These functions are needed to ensure that the MEU is fully equipped and protected for the mission. In order to analyze the MEU performance in A.1.2, logistics such as analyzing the fuel burn rate, resources used to setup command, and how often supplies are requested have to be collected. The energy analysis helped understand how renewable energy can be used in the field. Once the MEU is stationed at the shore site, the energy burn rate remains stable while the MEU is in standby mode. The resources needed at the shoresite helped to provide a good estimation of the electricity demand of the MEU for analysis. The request for supplies was also a function that is performed by the sustainement unit and captures how often

refueling is needed. Further breakdown of these functions can be found in Appendix A, and were used to aid the analysis of the USMC operations.

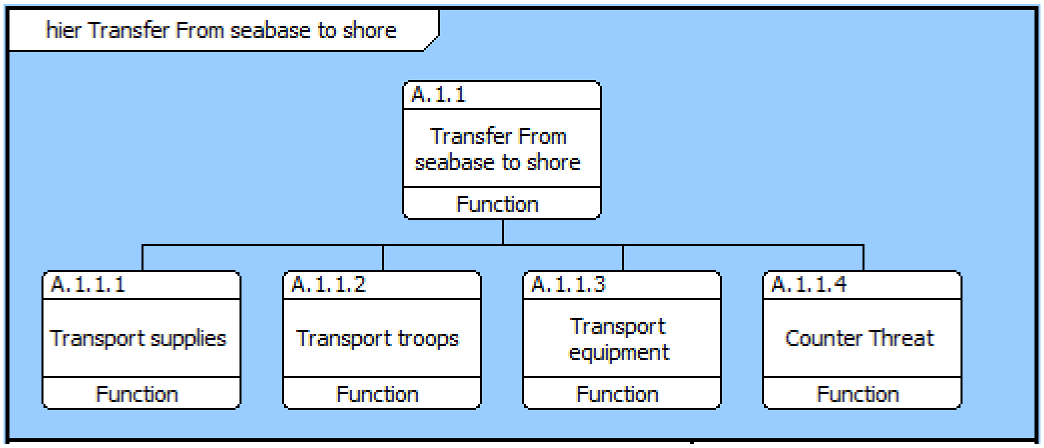

Figure 43. Breakdown of Function "Transfer from Seabase to Shore"

The sustainment portion of the capstone project is shown in Figure 44, the function "Provide shore site energy logistics" involved determining fuel burn rate, setting up command, and analyzing requested supply quantities. These functions established the logistics required of the MEU during sustainment and was used to analyze how much energy generated by renewable energy could offset the fuel burn rate of the MEU. The analysis of the fuel burn rate for the MEU focused primarily on the MEU MAGTF command element, with most MEU vehicles considered to be self-sustained. For this capstone project, the study focused on renewable energy sources for the MAGTF command element's energy needs. This capstone project explored the feasibility of adding to or replacing the MAGTF command element's diesel generators with renewable energy sources to reduce the demand for fossil fuels at the shore site. The energy consumed during the assembly of the MAGTF command element is also included as a function for obtaining these logistic benchmarks. Most of the energy utilized setting up camp involves vehicles which use diesel engines. The supply requests helped to analyze how much supplies and/or fuel is requested for a period of time, this function helped the capstone team understand how many trips a connector needs to perform during sustainment operations.

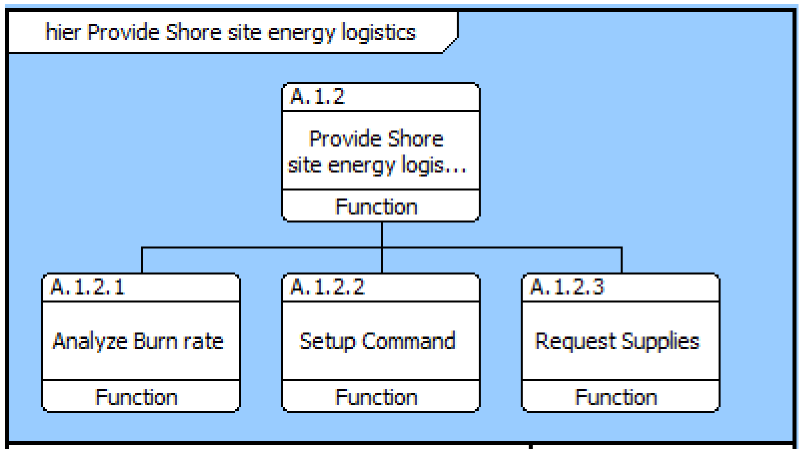

Figure 44. Breakdown of Function “Provide Short Site Energy Logistics”

As previously mentioned, the function “Perform USMC Expeditionary Simulations” emulates the function “Perform USMC Expeditionary Operations,” the sub-functions are very similar. Figure 45, shows the decomposition of the function “Perform USMC Expeditionary Simulations.” This decomposition helped the capstone team to create the simulation models. Each function had a different type of analyses conducted which is why they were separated. The function “perform mission” is not studied in this capstone project and is recommended for future capstone projects.

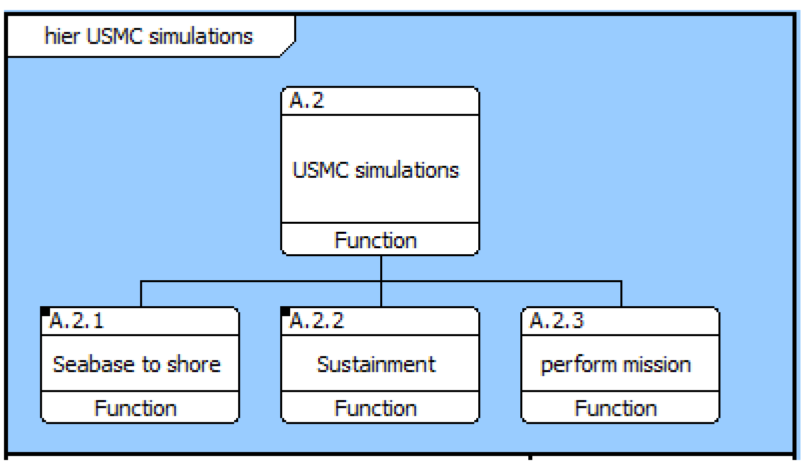

Figure 45. Breakdown of Function “Perform USMC Expeditionary Simulations”

The function “Seabase to shore” under the simulation function is different from the “Perform USMC Expeditionary Operations” function because it is focused on model and simulation efforts rather than the detailed sub-function efforts of the operations. These sub-functions, shown in Figure 46, include the simulation tool that was used, ExtendSim, and all the appropriate steps to complete the function. These steps include getting the software initialized, running the software, obtaining results, and the final analysis of those results.

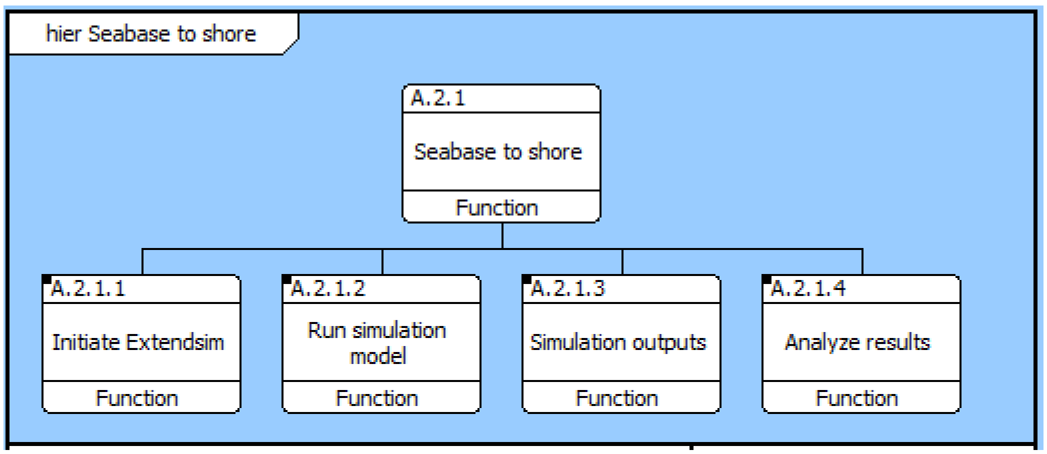

Figure 46. Breakdown of Function “Seabase to Shore”

The sustainment portion of the simulation use MPEM, a different software tool that better fit the analysis done at the shore site. The sustainment portion was studied to obtain information that would indicate renewable energy can be used. The function “Sustainment” in Figure 47, shows the utilization of the MPEM software tool. The sub-functions required for proper operation include initializing the parameters, constructing the organization, the scenario, the reports needed, and obtaining results. The MPEM tool allows each function to be conducted and was captured in the architecture. These functions are needed to complete the sustainment portion of this capstone project’s scenario.

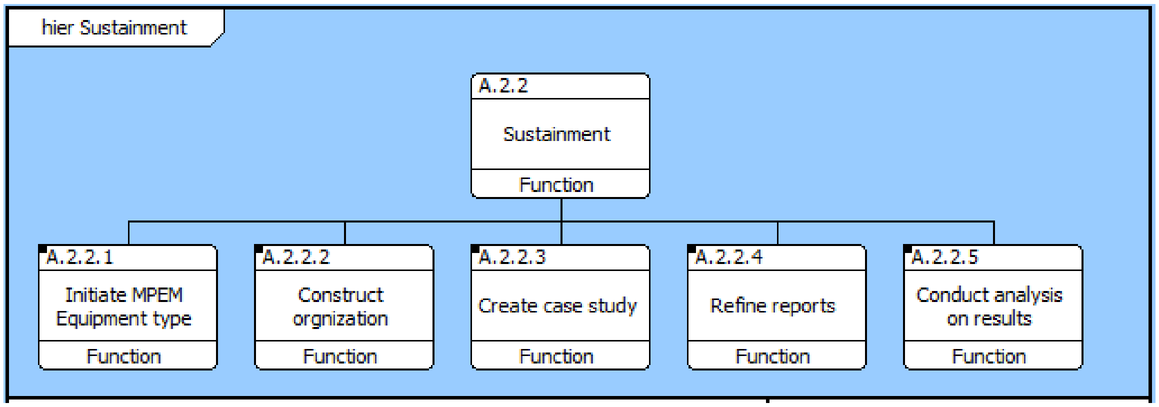

Figure 47. Breakdown of Function "Sustainment"

The decomposition of the top-level function helped discover most if not all of the functions needed to complete the study. The simulation decompositions helped break out the steps on how to conduct the simulation effort. In addition, it helped understand how to breakdown both the "seabase-to-shore" and the "sustainment" efforts. The architecture selected helped correlate the simulation effort with the USMC operations. After the decomposition of each function was established, understanding how each sub-function relates to another provided addition information for simulation.

2. Functional Flow Breakdown

To understand how each function was related to another, an EFFBD was used to display that relationship. Figure 48 shows one of the top-level functions "Perform USMC Expeditionary Operations" with the sub-functions relationships. As shown in the figure, "Transfer From Seabase to Shore," "Provide Shore Site Energy Logistics," "Transfer From Shore Site to FOM Land Site," and "Conduct Mission" are executed in sequential order. Understanding that these functions are not fully coupled allowed different simulation efforts to happen. Since this capstone study only captured the first two sub-functions, the results can be used to continue the study of the other two functions. More detailed information can be found in Appendix A for relationships of sub-functions.

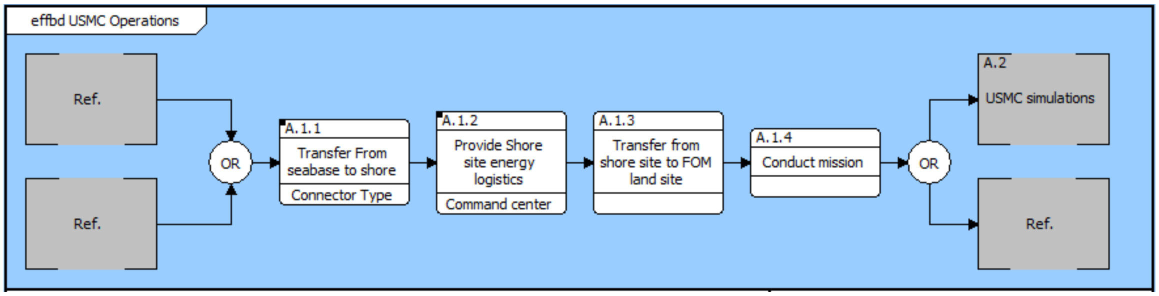

Figure 48. Function Flow of Perform USMC Expeditionary Operations

With the mission decomposed, each element or function is needed to be modeled in a simulation. The simulation model is decomposed into the sub-functions shown in Figure 49. These functions are related to the USMC operations and have the same sequential order. As previously mentioned, the main focus of the simulation is in A.2.1, "sea base to shore," and A.2.2, "sustainment." The function "Perform mission" captures both of the efforts not studied in the capstone project shown on the previous figure. By mimicking the Marine Corps Expeditionary operations, each simulation effort was conducted independently without needing the results from the other.

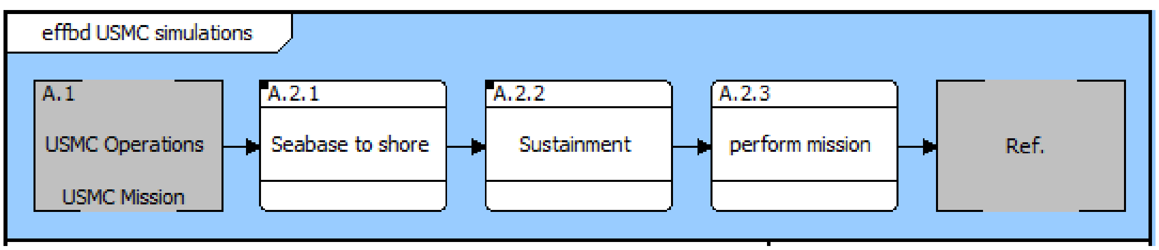

Figure 49. Function Flow of Perform USMC Expeditionary Simulations

The function A.2.1 was decomposed further to include actions needed to run the model properly. As shown in Figure 50, the overall steps on how to get the model running are shown. The first step to getting ExtendSim running is to initiate all the variables. This function allowed the programmer to set the parameters for the scenario into the model. After initaiting the model, creating the scenario in the model for execution was needed. After the execution of the model, the results would need to be captured in a format that can than be analyized. JMP Pro is used to analyze the results

after the execution of the model. Each of these functions has sub-functions that can be found in Appendix A.

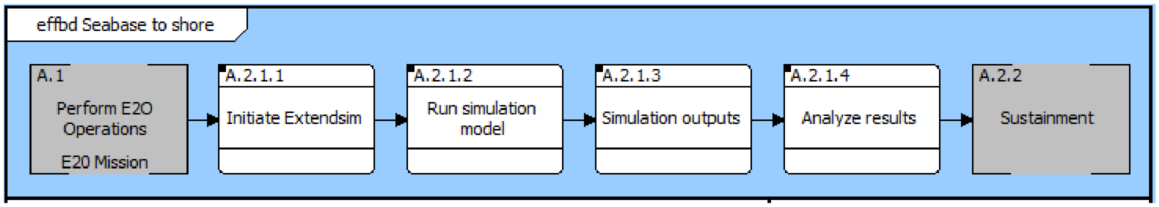

Figure 50. Seabase-to-Shore Functional Flow Block Diagram

The relationship of the function "Sustainment" can be seen in Figure 51, which shows the initiation of the MPEM simulation software. The first step within MPEM was to initiate the equipment list of the MEU and its organization at the command site. The input requirement for the model included the location and temperature information of the scenario. In order to extract the results, a report format was constructed that is compatible with the analysis software tool, and the results were analysed for the sustainment effort using renewable energy sources that best fit the warfare environment. The results of the model were analyzed to see the potential use of renewable energy sources.

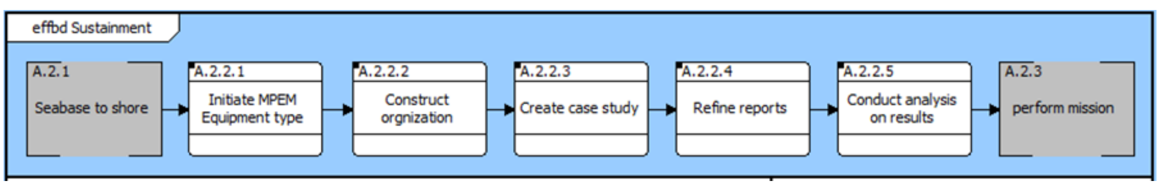

Figure 51. Sustainment Functional Flow Block Diagram

As shown in the previous figures, each function was related to the software tool used in the simulation which helped to create the steps needed to run the simulation models. Additional steps for each function can be seen in Appendix A, for the purpose of this report only the overview functions were shown. The architecture shown was the final layout that was used to complete this capstone project effort. Initially there was a lot of rework performed on the architecture as it was refined through the process. Overall, this

architecture helped find the path to get significant results needed to answer the research questions.

B. SYSTEM PHYSICAL ARCHITECTURE

The physical architecture for this capstone project included the Marine expeditionary unit (MEU), amphibious ready group (ARG), shore type, seashore connectors, supplies, and A2/AD threat. The team considered all components in the M&S effort performed during this capstone project. Each component was mapped to a function that the simulation was performing. As shown in Figure 52, the components were grouped into four categories.

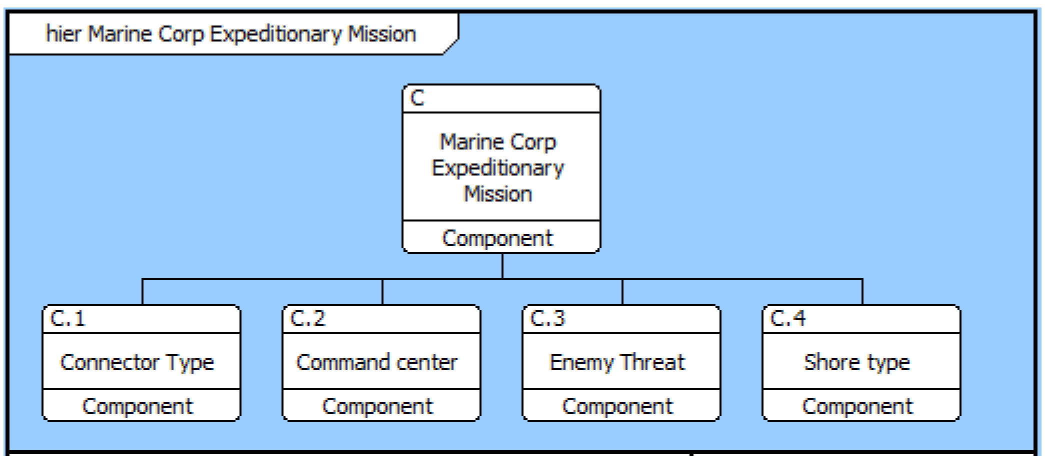

Figure 52. USMC Mission Physical Component Hierarchy

C. FUNCTIONAL TO PHYSICAL ARCHITECTURE MAPPING

The functional and physical architecture were mapped using Vitech CORE software. The software allowed direct traceability to requirements from functions and components needed for the system. CORE displays these relationships through the use of an Enhanced Functional Flow Block Diagram (EFFBD). This chapter will utilize these models for displaying the relationships between the components and functions.

From the overview of the function for the scenario, the main four functions are shown in Figure 53. The figure also shows the relationship to the components used for

these functions under the function block. The function "transfer from seabase to shore" utilizes the connector type components to perform these functions. Then, the function "Provide shore site energy logistic" is performed by the command element (CE) component. These relationships are shown for sub-functions in the architecture.

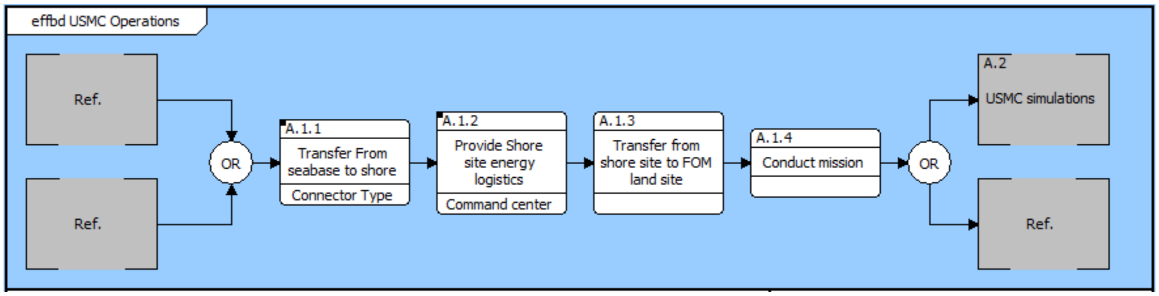

Figure 53. Functional Flow Block Diagram of the Perform USMC Expeditionary Operations Hierarchy

The sub-functions of "transport from seabase to shore" utilize the connector type components throughout. Figure 54 shows how transporting supplies, troops, and equipment are related to the connector type component. Even though there are other interactions with other components such as the ARG, these functions are primarily conducted by the connector type. Interaction to the ARG and the shore were assumed transparent to the model as stated in the assumptions section of this report.

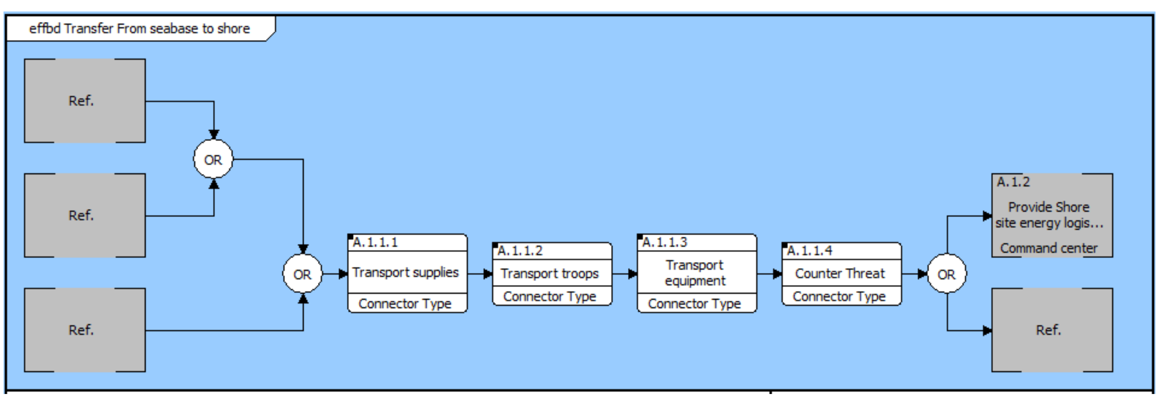

Figure 54. Seabase-to-Shore Function Relation to Physical Components

The sub-functions shown in Figure 55, Figure 56, and Figure 57 are performed by the connector type. The reason these functions were shown was to demonstrate how other components are used in sub-functions. Figure 58 shows how the enemy component is performed in the counter threat function. To counter the threat, the enemy has to be present and the communication between the connector type and ARG exists. Most of the functions within the counter threat function are performed by the connector type except when the threat fires.

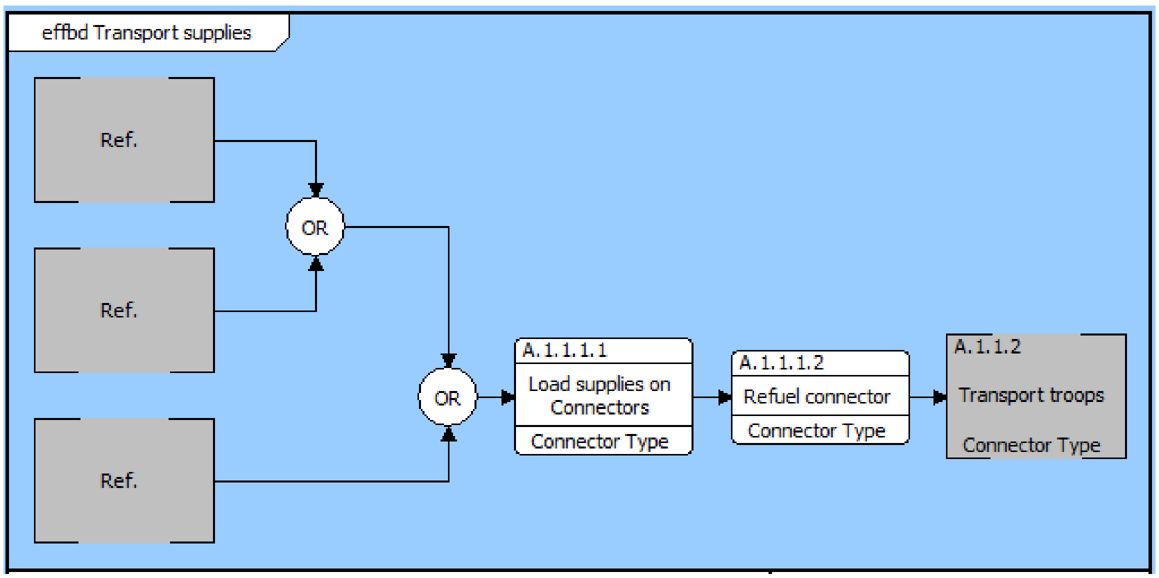

Figure 55. Transport Supply Function Relation to Physical Component

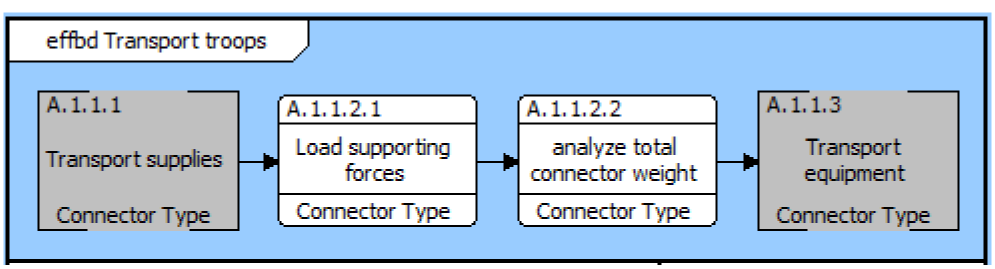

Figure 56. Transport Troop Function Relation to Physical Component

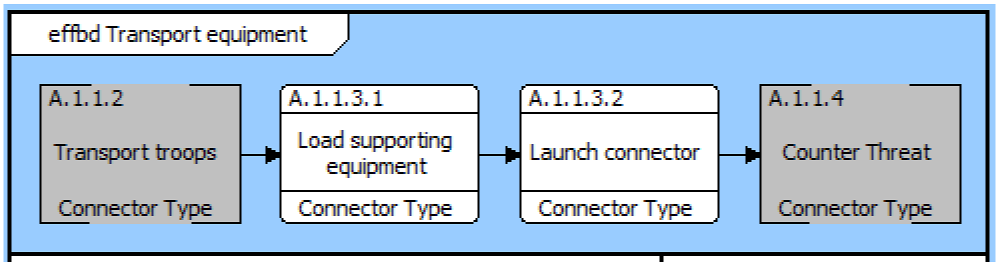

Figure 57. Transport Equipment Function Relation to Physical Component

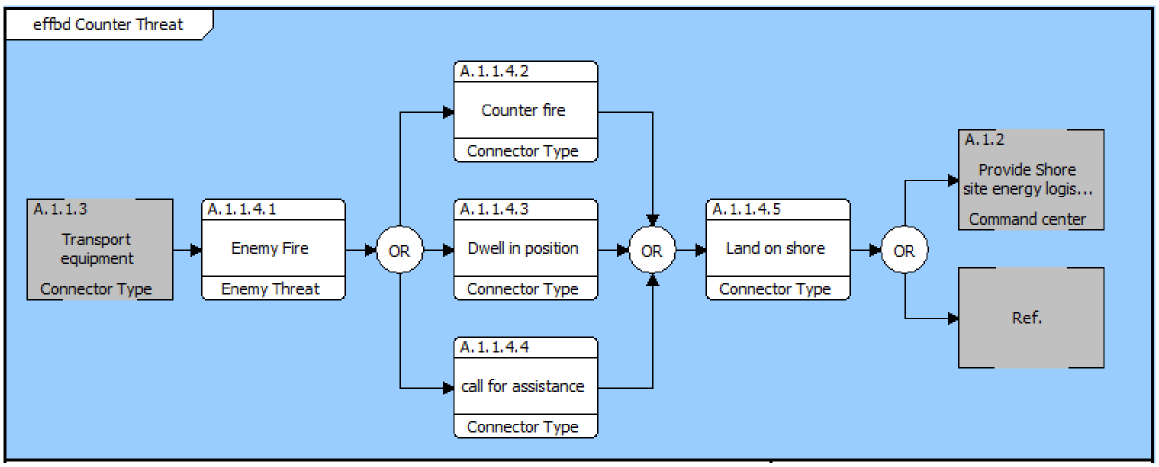

Figure 58. Counter Threat Function Relation to Physical Component

The second phase in the capstone project involved a shore site analysis of energy utilization. As shown in Figure 59, the functions are performed by the CE component. This capstone project used the Personnel and Equipment in a typical MEU to analyze the burn rate and reporting to the CE. The CE is the overall performer of each function.

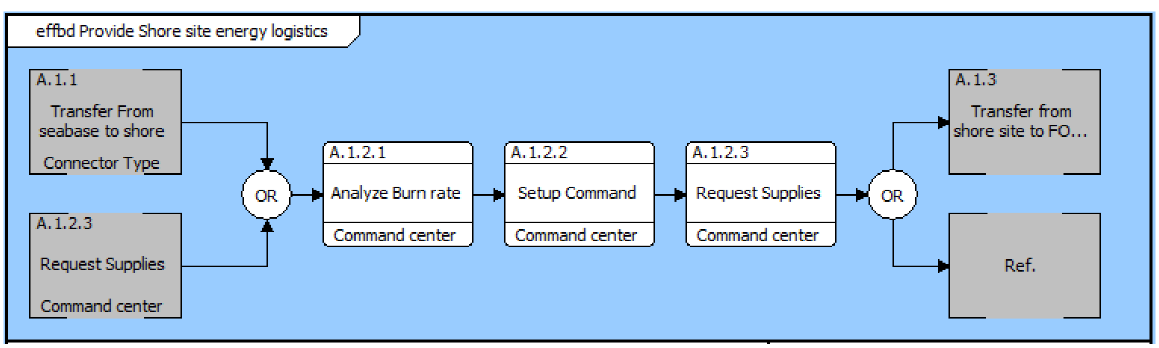

Figure 59. Sustainment Function Relation to Physical Component

The functions and component mapping enable traceability of each requirement to be shown. This ensures that each function specified is used and is aiming to complete the overall objective in the capstone project. By viewing the relationship between component and functions, it is possible to see any missed functions that were required. As stated, the components were properly mapped to each designated function and shown through the Vitech CORE EFFBD.

D. EXTENDSIM ARCHITECTURE

Function A.2.1.1 consists of the functions needed to get the model ready for sea base to shore exploration. As shown in Figure 60, the initialization of the ExtendSim software starts by defining the input to the model. The model initiates the equations and constructs surface connectors while managing each departure.

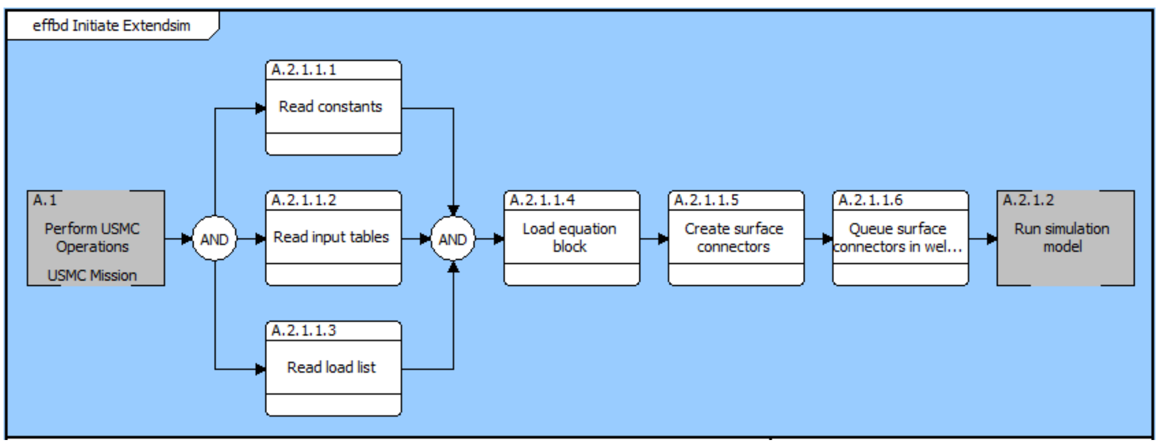

Figure 60. ExtendSim Initialization Flow

Function A.2.1.2 is decomposed to show the functions needed to be performed to run the simulation model. This simulation model followed the context diagram relating to the operation. Figure 61 shows an overview of the functions that are used in the model to bring the MEU to shore. The main focus of this figure is the loop that conducts all the launching of the connectors. A list of conditions need to be met before the simulation launches another connector.The detailed description of the flow of the modeling is described in the simulation section of this Casptone report.

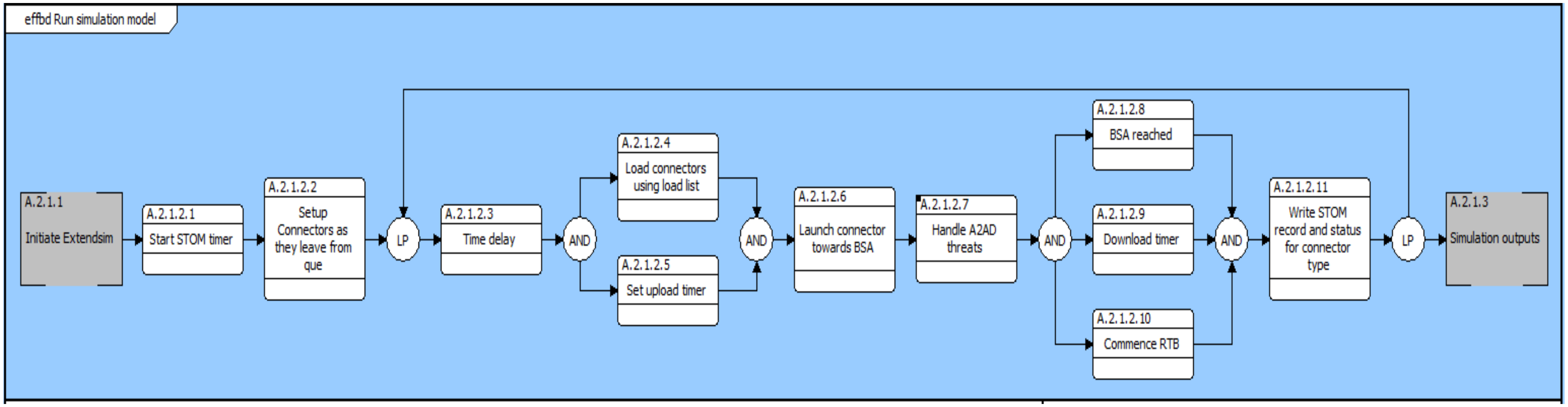

Figure 61. Simulation Run Flow

Function A.2.1.3 is the function needed for after the simulation is run. This function will write the model results to an output table which can be accessed by the team to perform the design of experiments (DOE). Figure 62 shows the flow for saving these outputs.

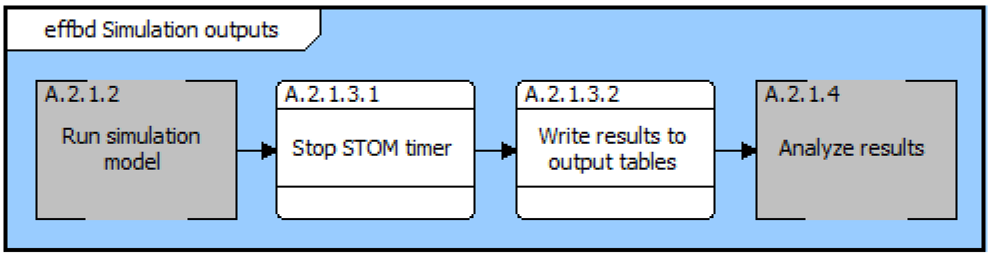

Figure 62. Simulation Output Functions

Function A.2.1.4 is needed to analyze the output of the simulation run. The function is decomposed into functions that will utilize other software to finalize the model outputs. Figure 63 shows the flow of the analysis function which utilizes JMP Pro.

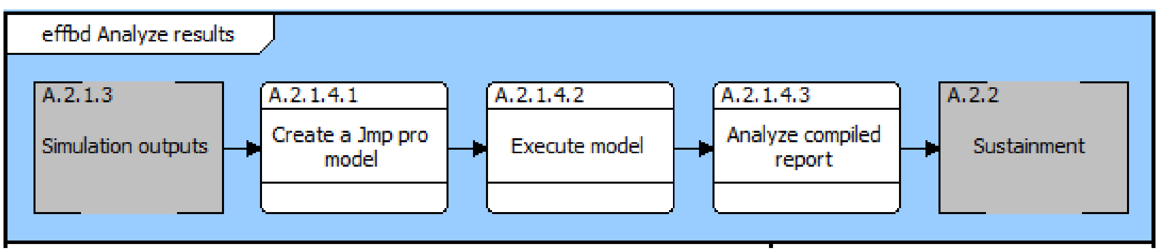

Figure 63. Analyzing the Output of the Simulation Through JMP Pro

The sustainment simulation focused on utilizing renewable energy sources to lower fossil fuel dependency. As shown in Figure 64, the functions required to complete the analysis have been arranged in a sequential order. This simulation utilized the MPEM tool for conducting how much fuel was utilized by the MEU.

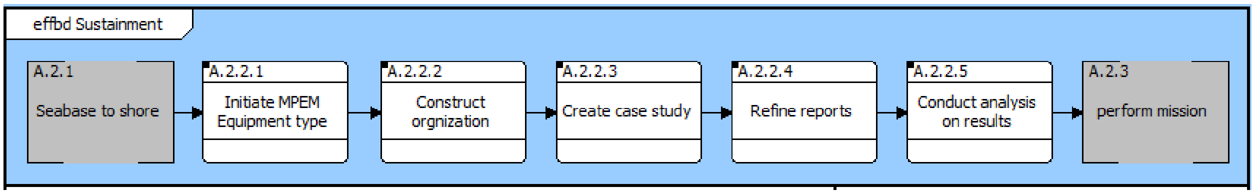

Figure 64. Analysis of Sustainment Operation Simulation Through MPEM

To initiate the MPEM model, the creation of the renewable energy sources had to be created into the database. The functions displayed in Figure 65, show the creation of these parameters into MPEM.

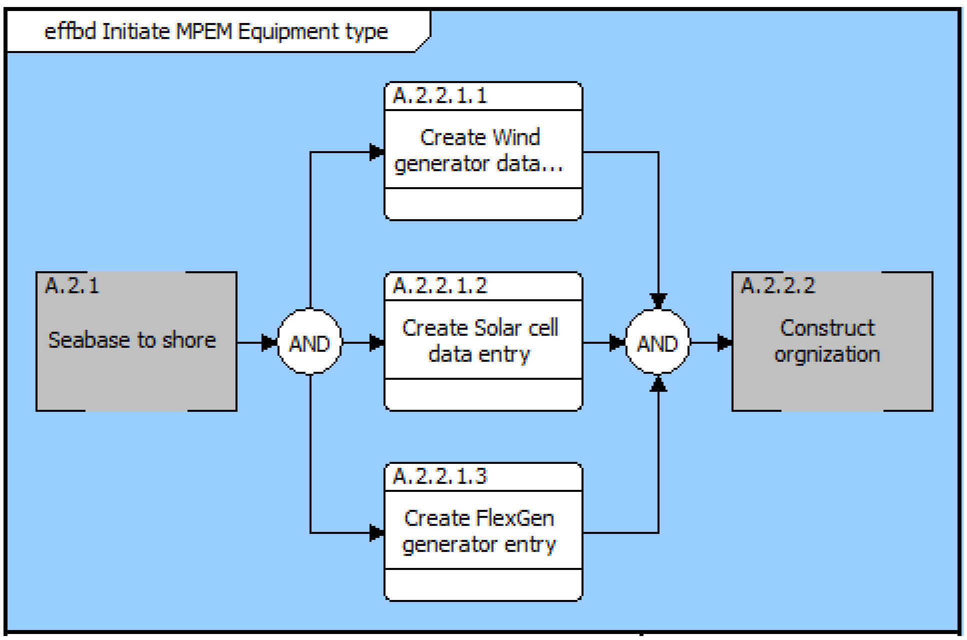

Figure 65. Creation of MPEM Parameter

Constructing the organization in for use in the study is needed to run the MPEM model. As shown in Figure 66, constructing the MEU and assigning the renewable energy equipment to them was required for the study. These functions will allow the proper parameters to be set into the MPEM model.

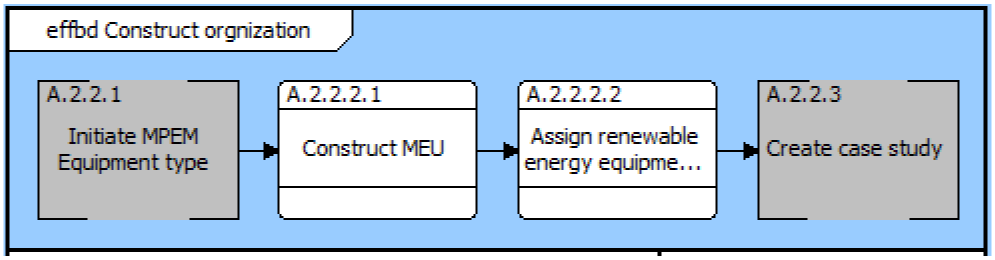

Figure 66. Sub-flow of A.2.2.2

The case study must be constructed next in MPEM. Using the MPEM user guide allowed the team to set the organization, location, and scenario construction into the model. Figure 67 shows the functions required to create the case study in MPEM. In the sustainment portion of the report, additional details on the what parameters were set in MPEM will be discussed.

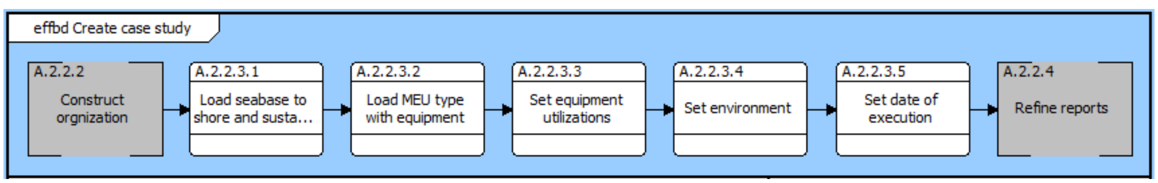

Figure 67. Functions Required to Create Case Study in MPEM

To analyze the MPEM results, MPEM has to be set to create reports of the results. Figure 68, shows the functions needed to set MPEM to create the reports needed for analysis. The reports needed are relating to the renewable energy sources and the fuel consumption of the MEU.

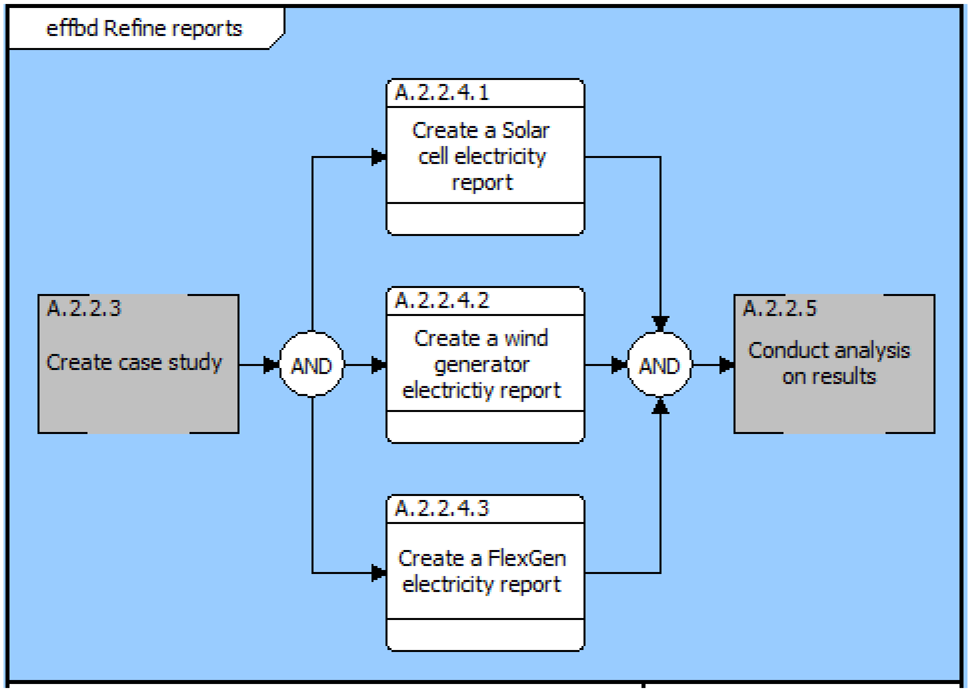

Figure 68. Functions to be Set in MPEM

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APPENDIX C. MODELING AND SIMULATION DETAILS, MOES AND MOPS

This Appendix delineates how ExtendSim was used, how the MOEs and MOPs were derived and tested, and what were used as measures.

A. EXTENDSIM MODELING DETAILS

The E2O STOM model was built using ExtendSim Suite 9.2 and was updated using the v9.2 updater application. The model shown in Figure 69 appears simple on the surface but hides a significant amount of ModL code. ModL is the ExtendSim programming language, structured much like C++, and is executed within an Equation block highlighted in Figure 69.

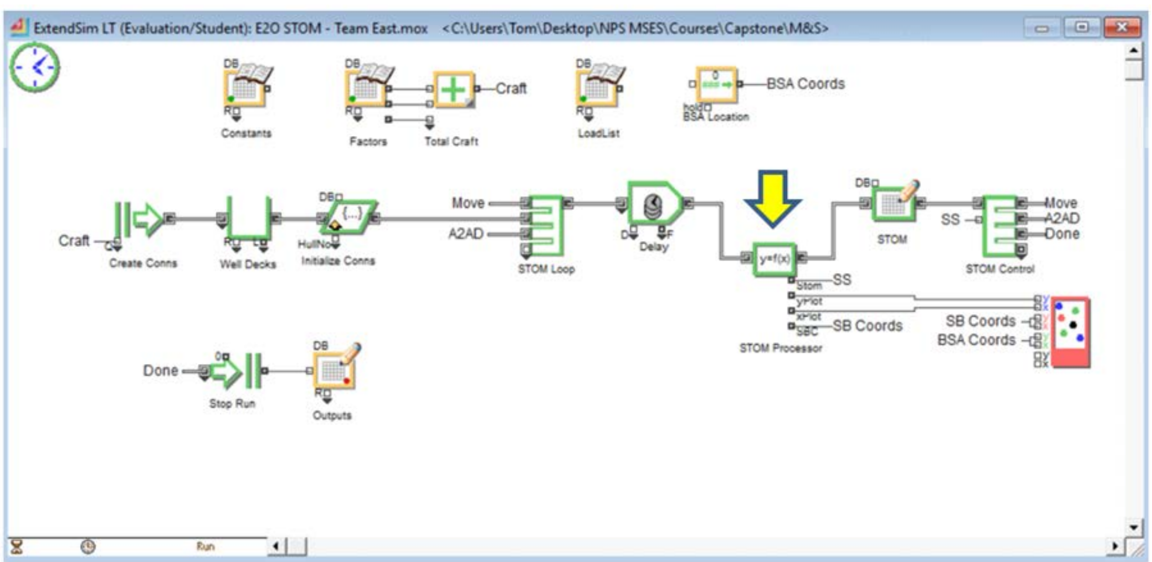


Figure 69. E2O STOM Model

The model functional architecture was developed using CORE and is documented in others areas of this report. The functional architecture also contributed to the STOM model processing flow shown in Figure 69. The model flows from left to right where surface connectors (craft) are created, held in the well-decks queue, shifted right to the

Set block where the craft are preloaded with fuel and a portion of the initial mission module for the GCE, and then set with a hull number of -1 to signal a new craft is entering the main STOM Processor loop. The craft leaves the STOM Loop Select block to the right and is held in the Activity block to create a superficial time delay before it enters the Equation block.

The Equation block performs all of the sophisticated processing for the model including reading and writing of all database tables. The surface connectors are initialized, reloaded with mission module portions, moved according to speed, direction of intended movement, and time. The Equation block populates fields in the STOM table that record current time, position, speed, craft status, fuel remaining, and distance to destination. A new STOM record is written for each connector every time a craft exits the Equation block. If an A2/AD event occurs during the STOM, the processing within the Equation block is modified to implement the preprogrammed behaviors described in section 1A of this chapter.

The Equation block also downloads mission modules when the craft reaches the LZ, returns the craft back to the seabase for uploading, and refuels the craft when a "bingo" state is reached. This processing repeats until all mission modules from the Load List table are transferred from the seabase to the shore. When a STOM completes, a status of "Done" is set in the main loop which causes all craft to be refueled and stowed back on their respective ships, a STOM summary record is written to the Outputs table which concludes a single simulation run for the model.

The final portion of model construction involved the integration of the 27 distinct scenarios that allowed trade-off analysis between different the fuel saving alternatives identified by the capstone team and the stakeholders. The model has some stochastic system properties that allowed for improved exploration of the trade space. The model used 14 input factors that were configured in 65 distinct combinations. These factor combinations, when applied to the 27 distinct scenarios, bounded by a three-ship ARG, were multiplied by a replication factor of 30 to produce an optimum simulation run count of 52,650.

B. MEASURES OF EFFECTIVENESS

Measures establish critical parameters of a project and describe how they will be evaluated against the success of that project. Each partition of the capstone project had different measures to reflect how the units were used. The performance of each measure was seen from the modeling and simulation conducted. In order to derive the measures, the scenario needed to be fully developed and fully described. Figure 70 shows the relationship between the scenario, KPPs, and measures.

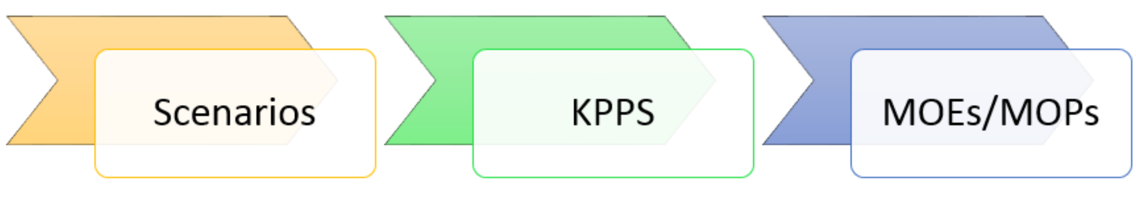


Figure 70. Scenarios to Measures Progression

As shown in Figure 70, the scenarios help defined and identify the KPPs that subsequently determine MOEs that are assessed using metrics. The measures are required to assess and achieve the MOE. The appendix focuses on the energy KPP from the JCIDS manual and further considers the Force Protection and Survivability KPPs. The MOEs that the team defined were explored in simulations and analyzed to help understand the energy KPP.

Two MOEs were developed to define the metrics used to assess capability performance. The MOEs were further defined using measures, which must be satisfied to achieve the MOEs. The MOEs were aligned, when possible, with the Marine Corps Tasks (MCTs) as shown in the Marine Corps Task List (MCTL). The threshold and objective values for each measure were used to develop input factors and set their respective range of variation for the modeling and simulation (M&S) effort.

The first MOEs assess the capability of an MEU to effectively move its assets from the seabase to the shore. The second MOEs focused on the reduction of fuel during an A2/AD scenario within a non-traditional environment against a non-traditional threat.

These MOE's considered the amount of fuel consumed by a shore based Marine air-ground task force (MAGTF) power grid during setup and initialization. The transport, setup, and initialization of the MAGTF is assumed to take 72 hours (three days) and includes enough supplies to complete initial operation.

1. Measures for the Seabase-to-Shore MOE

Table 13 shows the first MOE and its subsequent measures. The capstone team used these measures to support the assessment of energy efficiency of the amphibious surface connectors operating during a STOM. This MOE assessed the capability of a MEU MAGTF to effectively transfer from the seabase to the shore. Currently the seabase-to-shore operations are accomplished using fuel to for the surface connectors (Skahen et al. 2013).

Table 13. STOM Model Measures

Throughput of a surface connector system that transports an MEU from SB to shore			
Measure	**Type**	**Description of Measure**	**Factor Range**
M1	Number	Of craft to conduct offload	6-9
M2	NM	Distance required to move	12, 18, 24
M3	Percent	Of surface connector payload capacity	50 / 100
M4	Tons/Minute	Rate of craft loading	1.4-6.9
M5	Sea State	Capable of conducting offload	1-3
M6	Yes/No	Fire Support Plan coordinated	Yes/No

M1 describes the number of surface connectors that are operating concurrently to transport the MAGTF elements from seabase-to-shore. The number of connectors is limited by a three-ship ARG where the connector type embarkation requirements are known. The LCAT connector embarkation requirements are assumed to be similar to an LCAC. A test case for this measure must result in time to complete and fuel consumption changes.

M2 describes the distance the surface craft are required to travel in nautical miles (NM). The seabase standoff measures that determine craft travel distance are 12, 18 and

24 NM, and were provided by the E2O. A test case must result in a correlation where change in distance results in a change in time to complete and fuel consumed.

M3 describes the percentage of payload capacity the surface connector is permitted to transport. This is a controlled measure designed to explore changes in loading time due to payload limit. Change in fuel consumption was not explored due to lack of craft power curves. A test case must demonstrate that a decrease in payload capacity results in an increase in loading rate. The same inverse relationship is true for an increase in payload capacity.

M4 describes the rate at which the surface connectors can be loaded in tons/minute. The loading rate varies from 1.4 to 6.9 tons/minute and changes due to upload/download status, available craft deck space and payload weight limitations due to element packing density or payload capacity limitations defined by M3. A craft loading status of upload means the process of loading MAGTF mission package material on to a surface connector where download means the process of removing the loaded material from the connector. A test case must demonstrate that the craft loading rate varies due to the aforementioned.

M5 describes an uncontrollable input factor called sea state. The sea state has an effect on surface connector stability which in turn slows the connector speed while fuel consumption remains constant. The net effect of the sea state was a change in surface connector speed that limited distance traveled per gallon of fuel. Speed limiters for each connector type were calculated for sea state values one, two, and three using a sea state table for LCAC operations (MCRP 3–31.1A 1997, 8–8). The effects of sea state on LCAC were extended to LCU and LCAT by a formula in support of the conceptual model. Sea states above three were not calculated due to increased risk of STOM operations. Results from sea state zero are assumed to be similar to sea state 1. A test case for sea state must result in a speed limiter that correlates to each sea state increment.

M6 describes the fire support plan used before and during the STOM. This plan mitigates risk that stems from the A2/AD environment. The beach head is prepared to facilitate safe landing prior to commencing the STOM mission. In the event an A2/AD

event occurs during the STOM, the fire support plan has predefined actions that are taken to mitigate the threat. A test case for this measure must result in additional time to complete and is based on the number of threat events encountered during the STOM.

Figure 71 shows a notional STOM in support of MOE #1 that was simulated using a software modeling application called ExtendSim. This model simulates the transfer of the MEU MAGTF equipment and personnel from seabase to shore by simulating activities that occur in the three different zones. Zone one is a safe zone near the seabase that is used to upload and download equipment and personnel between the surface connectors and the seabase. Zone two shows the inner transport zone where the surface connectors define their approach and traverse most of the open water. Zone three shows a danger zone where A2/AD tactics from hostile groups may be encountered. CAS and CAP sorties may be required while the MEU MAGTF GCE establishes and secures a perimeter a short distance inland.

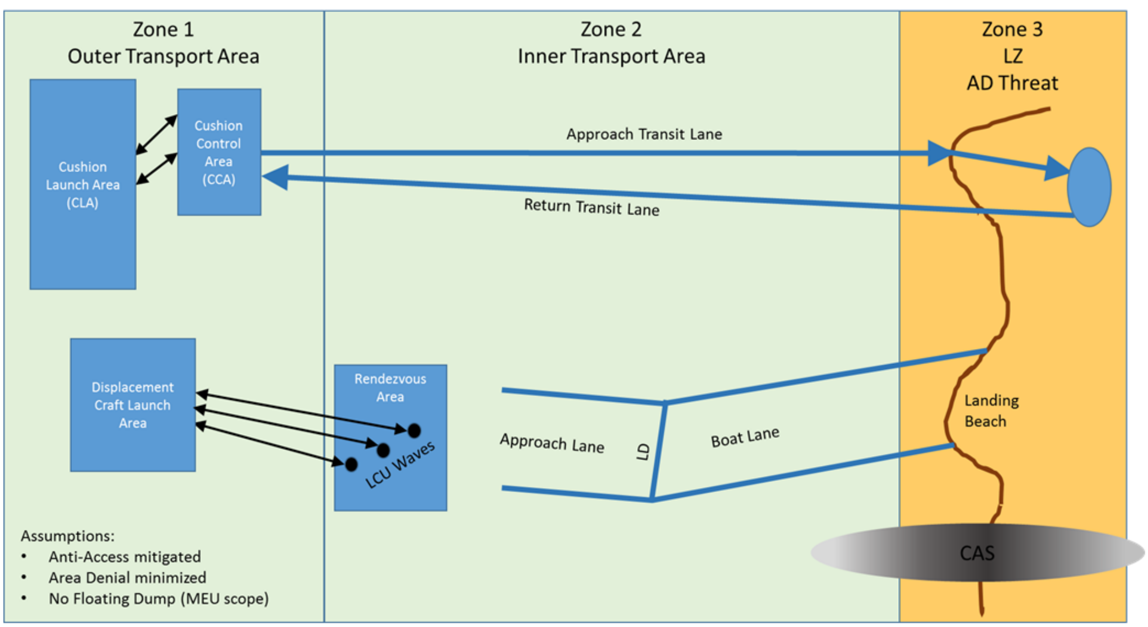


Figure 71. Notional STOM for MOE #1

Figure 72 shows the notional data structures and processing flow of the ExtendSim model. The figure was used to pseudocode the STOM model in ExtendSim and to verify the sequencing with the sponsor before the model was built and validated.

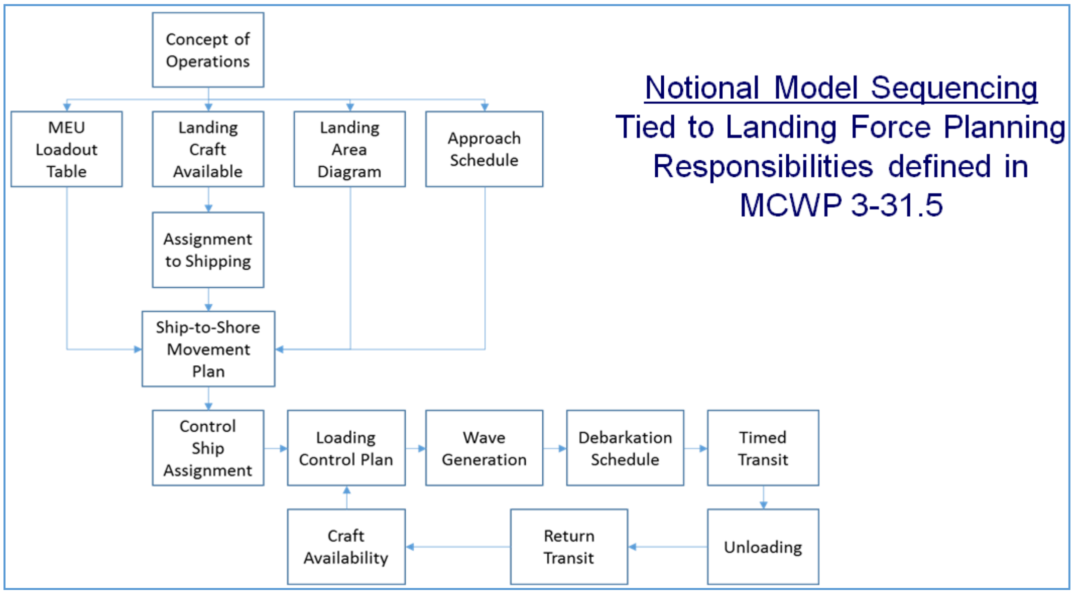


Figure 72. Notional ExtendSim Model Process Flow

2. Measures for Fuel Consumption

Table 14 shows the second MOE used to support the assessment of energy efficiency of the MEU MAGTF while operating ashore under an A2/AD condition as described in the second scenario. The scenario describes typical MEU MAGTF operations within a non-traditional environment against a non-traditional threat. This MOE considers the energy efficiency of a shore based power grid established during the setup and initialization of the MEU MAGTF. The transport, setup and initialization of the MEU MAGTF elements ashore is assumed to take 72 hours (three days) and includes enough supplies to complete initial operation. The capstone team explored the trade space of the seabase-to-shore system by creating a model of the current capabilities. The team then evaluated and changed each aspect of the model, and finally captured the effects of the alterations as a measure of energy efficiency over a period of time.

Table 14. Energy Efficiency of MAGTF Setup and Initialization While Operating Ashore

MEU fuel reduction during the setup and initialization of a shore based MAGTF			
Measure	**Type**	**Description of Measure**	**T / O**
M1	Number	Of Megawatt hours (mWh) of electrical power required	8.6 / 6.2
M2	Percent	Electrical power from alternative energy sources	28 / 40
M3	Number	Of diesel generators required to meet the demand	6 / 5
M4	Percent	Reduction in fuel storage capacity to meet MAGTF power demand	28 / 40

The measures have threshold and objective values that were vetted and approved by the stakeholders and used to drive input variation controlled by the design of experiments (DOE). Stakeholder requirements elicited while interacting with the sponsor were used to drive input variation in the simulation. The M&S effort derived inputs from the problem statement and scenarios were written to explore force operations with energy efficient alternatives. The model outputs are driven by the need for data analysis that produced information in support of the answers to the capstone project research questions.

The problem statement was decomposed to identify mandatory key performance parameters (KPPs) that are applicable to the capstone project as described in the Joint Capability Integration Development System (JCIDS) manual. The Force Protection, Survivability and Energy KPP descriptions align well with the problem statement and support the scenarios selected to explore energy efficient alternatives while maintaining operational effectiveness. A capability model was created using measures to estimate an acceptable level of performance required to maintain force operational effectiveness. Data from the MAGTF Power and Energy Model (MPEM) was used to create the current capability model. The capstone team created estimation data from industry standard calculations that were vetted and approved by the sponsor when data was not available in MPEM.

The capability model was verified and validated by presenting a demonstration and analysis data to the sponsor. Once the capability model outputs were reasonable and approved by the sponsor, changes were introduced to the model and a number of

simulations were run to produce data for pattern analysis. The capstone team used the outcomes from the pattern analysis to document findings, formulate answers to the capstone project research questions, and provide a basis for conclusions and recommendations.

These measures worked excellently for the study of the seabase-to-shore and sustainment. The team was able to utilize the factors in other simulations such as DOE to fully understand how much fossil fuel dependency can be reduced.

M1 describes the number of megawatt hours required to power the MAGTF force ashore. The threshold value of 8.6mWh was calculated using the MPEM to determine the amount of power needed to operate the electronic equipment, lighting, air conditioning, and utility power for each Marine required to sustain shore based MAGTF operations. This measure addresses power conservation without compromising operational effectiveness. The test case must address a 28% reduction in power consumption through energy conservation to achieve the MOP objective of 6.2mWh. The objective power reduction requirement of 28% traces to the USMC E2O initiatives for force operations of 40% efficiency gain by the year 2020 (USMC n.d.-b,22). The test case results must verify that an increase in energy conservation correlates to a reduction in fuel consumption.

M2 describes the E2O initiative to reduce force dependence on fuel by using electrical power from alternative energy sources. This measure, when combined with reduction of energy demand through conservation, delivers the capability to operate the force with lower dependence on fuel. The threshold amount of 28% traces to the USMC E2O initiatives for force operations of 40% drives considerations for future technology insertion (USMC n.d.-b, 25). The test case results must demonstrate a capability that meets the electrical power demand of the force using alternative energy sources that on average contribute no less than 28% and do not impact operational effectiveness.

M3 and M4 describe measures that correlate to M1 and M2. If M1 and M2 are achieved, M3 reduces the number of diesel generators required to meet the electrical power demand and thus reduces the fuel storage capacity requirement. The test case must demonstrate increased endurance by reducing the number of diesel generators and

improved mobility and reduced fuel truck convoys due to the decrease in fuel storage requirements.

3. Test Cases for the MOEs and Their Corresponding Measures

Each measure, to be effective, must be testable and its results must be qualifiable within the context of the system. For this capstone project, the test cases were captured as factors within the design of experiments (DOE). Table 1 and Table 2 describe two different MOEs for the project. The capstone team assessed the MOEs using the measures that had been defined to support each MOE. The MOEs did not require test cases and were assessed using qualitative analysis of the measures that support them. The test cases for each measure are described in the paragraphs that follow.

The MOE that defines throughput of a surface connector system that transports an MEU-sized MAGTF from seabase-to-shore includes all elements but the ACE which remains on the seabase. ExtendSim was used to model the transport of MAGTF elements from seabase-to-shore. The six measures defined to assess throughput of the surface connector system are indexed M1 through M6 as shown in Table 13

The MOE that defines MEU fuel reduction during setup and initialization of a shore based MAGTF includes all MAGTF elements but the ACE which remains on, and operates from, the seabase. The four measures defined to assess MEU fuel reduction are indexed M1 through M4 as shown in Table 14 .

APPENDIX D. DESIGN OF EXPERIMENTS RESULTS

This appendix goes into detail how the design of experiments (DOE) is performed, then continues with the scatterplot matrix that the capstone team created in JMP Pro to evaluate how well the design space was explored with the DOE design table. Specifically, the two-dimensional scatterplot matrix shows the design space that was explored with the various combinations of factors that are included in the DOE design table. Additionally, a three-dimensional scatterplot matrix is provided in this appendix to show the portion of the design space that was explored and not explored by the three factors that are related to the number of connectors (number of LCACs, LCUs, and LCATs). This appendix also includes a partial view of the DOE design table that was used as an input for the factors settings of the seabase-to-shore operational model.

A. DOE APPROACH

This capstone project used a hybrid design approach to investigate these eleven factors for each of the 27 possible combinations of connectors. Because of the bounded nature of the three ship ARG that is considered in this study, the scenarios resulted in a total of 1,755 simulation runs for a single replication of the experiment. Specifically, the hybrid approach took the 27 possible combinations of connectors for a three-ship ARG and merged them in JMP Pro with a traditional space filling design for the eleven factors that were generated using the NOLH designs spreadsheet. Then, the capstone team replicated the experiment thirty times (52,650 simulation runs) to have a sufficient number of tests at each design point. Thirty replications were chosen because that is the point where the t-distribution began to approximate the normal distribution. Figure 73 provides the correlation matrix that was created in JMP Pro for the resulting experimental design to determine the correlations of each factor. It is important to notice that the correlations are minimized between most of the factors, with a design goal to keep correlation to less than 10%. This goal was realized with the 11 factors that utilized the NOLH, but not the number of LCACs, LCUs, and LCATs.

Correlations

	LCAC_#	LCU_#	LCAT_#	LCAC_TI	LCAC_%L	LCU_TI	LCU_%L	LCAT_TI	LCAT_%L	SSD	SS	RPG	IED	SAF
LCAC_#	1.0000	-0.4970	-0.4617	0.0000	0.0000	0.0000	-0.0000	-0.0000	0.0000	-0.0000	-0.0000	0.0000	-0.0000	0.0000
LCU_#	-0.4970	1.0000	-0.5268	0.0000	-0.0000	0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	-0.0000	0.0000	-0.0000
LCAT_#	-0.4617	-0.5268	1.0000	-0.0000	0.0000	-0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
LCAC_TI	0.0000	0.0000	-0.0000	1.0000	-0.0152	0.0152	0.0251	0.0152	0.1256	0.0645	0.0213	0.0767	0.0152	-0.0464
LCAC_%L	0.0000	-0.0000	0.0000	-0.0152	1.0000	0.0251	0.0016	0.1055	0.0082	-0.1342	0.0493	-0.0353	0.0653	0.0049
LCU_TI	0.0000	0.0000	-0.0000	0.0152	0.0251	1.0000	0.0251	0.0152	-0.0353	0.0213	-0.0219	-0.0464	0.0152	0.0767
LCU_%L	-0.0000	-0.0000	0.0000	0.0251	0.0016	0.0251	1.0000	-0.0956	-0.0050	0.1198	0.1057	-0.0755	0.0251	0.1256
LCAT_TI	-0.0000	-0.0000	0.0000	0.0152	0.1055	0.0152	-0.0956	1.0000	0.0854	0.1077	-0.0219	0.0767	0.0152	-0.0464
LCAT_%L	0.0000	-0.0000	0.0000	0.1256	0.0082	-0.0353	-0.0050	0.0854	1.0000	0.0493	-0.0495	0.0251	0.1658	-0.1760
SSD	-0.0000	-0.0000	0.0000	0.0645	-0.1342	0.0213	0.1198	0.1077	0.0493	1.0000	0.1208	-0.1083	0.1077	0.1941
SS	-0.0000	-0.0000	0.0000	0.0213	0.0493	-0.0219	0.1057	-0.0219	-0.0495	0.1208	1.0000	-0.0651	0.1077	-0.0651
RPG	0.0000	-0.0000	0.0000	0.0767	-0.0353	-0.0464	-0.0755	0.0767	0.0251	-0.1083	-0.0651	1.0000	0.0767	0.0152
IED	-0.0000	0.0000	0.0000	0.0152	0.0653	0.0152	0.0251	0.0152	0.1658	0.1077	0.1077	0.0767	1.0000	0.0767
SAF	0.0000	-0.0000	0.0000	-0.0464	0.0049	0.0767	0.1256	-0.0464	-0.1760	0.1941	-0.0651	0.0152	0.0767	1.0000

Figure 73. Correlation Matrix for the Resulting Design

As mentioned previously, the correlations are minimized between most of the factors, however the correlations between the number of LCACs, LCUs, and LCATs was around 50%. This is due to the 27 fixed connector combinations that comprised all the realistic configurations that would fit in the well-decks of a three-ship ARG. This resulted in a limited number of design points that would be analyzed by the capstone team for connector scenarios. A scatterplot matrix was created in JMP Pro to assess how well the design space was explored in this capstone project. Additionally, a 3D scatter plot was created in JMP Pro to evaluate in a three-dimensional view how well the shared design space for the combinations of connectors was investigated. Figure 74 shows a section of the scatterplot matrix that presents a visual representation of the portion of the design space that was not explored. Specifically, the upper right portion of the shared design space where the number of LCACs, LCUs, and LCATs are maximized is nearly empty due to the limited number of design points that were investigated for these three factors. However, failing to investigate the upper right portion of the shared design space where the combinations of connectors are maximized is not adequate from a statistical standpoint, the capstone team felt that limiting the investigation in this study to just feasible combinations of connectors for a three-ship ARG outweighed the slight statistical compromise for the combination of connectors.

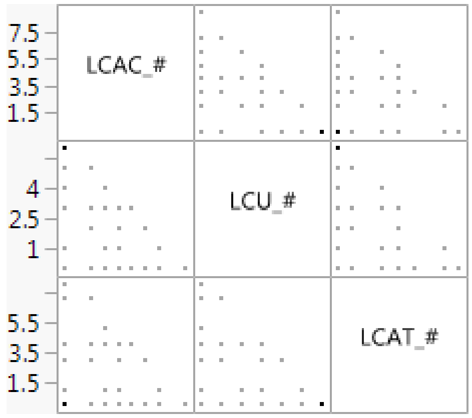


Figure 74. Portion of the Design Space That Is Not Explored

The team used the DOE methodology to develop an experimental design with selected combinations of factors to properly investigate the responses of the seabase-to-shore operational scenario. The four responses that were explored for the seabase-to-shore operational scenario are the Mission Payload Transfer Time (MPTT), Total Fuel Used (TFU), Total Loiter Time (TLT), and the Average Speed (AS) of the connectors. As mentioned earlier in this section, the team took the 27 possible combinations of connectors for a three-ship ARG and merged them in JMP Pro with a traditional space filling design for the eleven factors that were generated using the NOLH designs spreadsheet. This step was performed to create a table in JMP Pro with experimental values for all 52,650 of the required simulation runs. Then, these values were copied directly to the database of the seabase-to-shore operational model and the team ran the simulation according to the factors that were included in each of the 52,650 simulation runs. As soon as the simulations runs ended, the team proceeded to copy the values of the responses for each simulation run to the original table in JMP Pro that contained the value of each factor for the 52,650 simulation runs. This is the point when the capstone team could use the completed table in JMP Pro to run the statistical analysis for the data obtained.

B. SCATTERPLOT MATRIX

The capstone team used JMP Pro to create a scatterplot matrix as a way to evaluate how well the design space was explored in this capstone project. Figure 75

illustrates the scatterplot matrix that provides a visual representation of the design space that was explored in the capstone project. It is important to notice that failing to investigate the upper right portion of the shared design space where the combinations of connectors are maximized is not adequate from a statistical standpoint. However, the capstone team felt that restricting the investigation in this study to only feasible combinations of connectors for a three-ship ARG outweighed the slight statistical compromise for the combination of connectors.

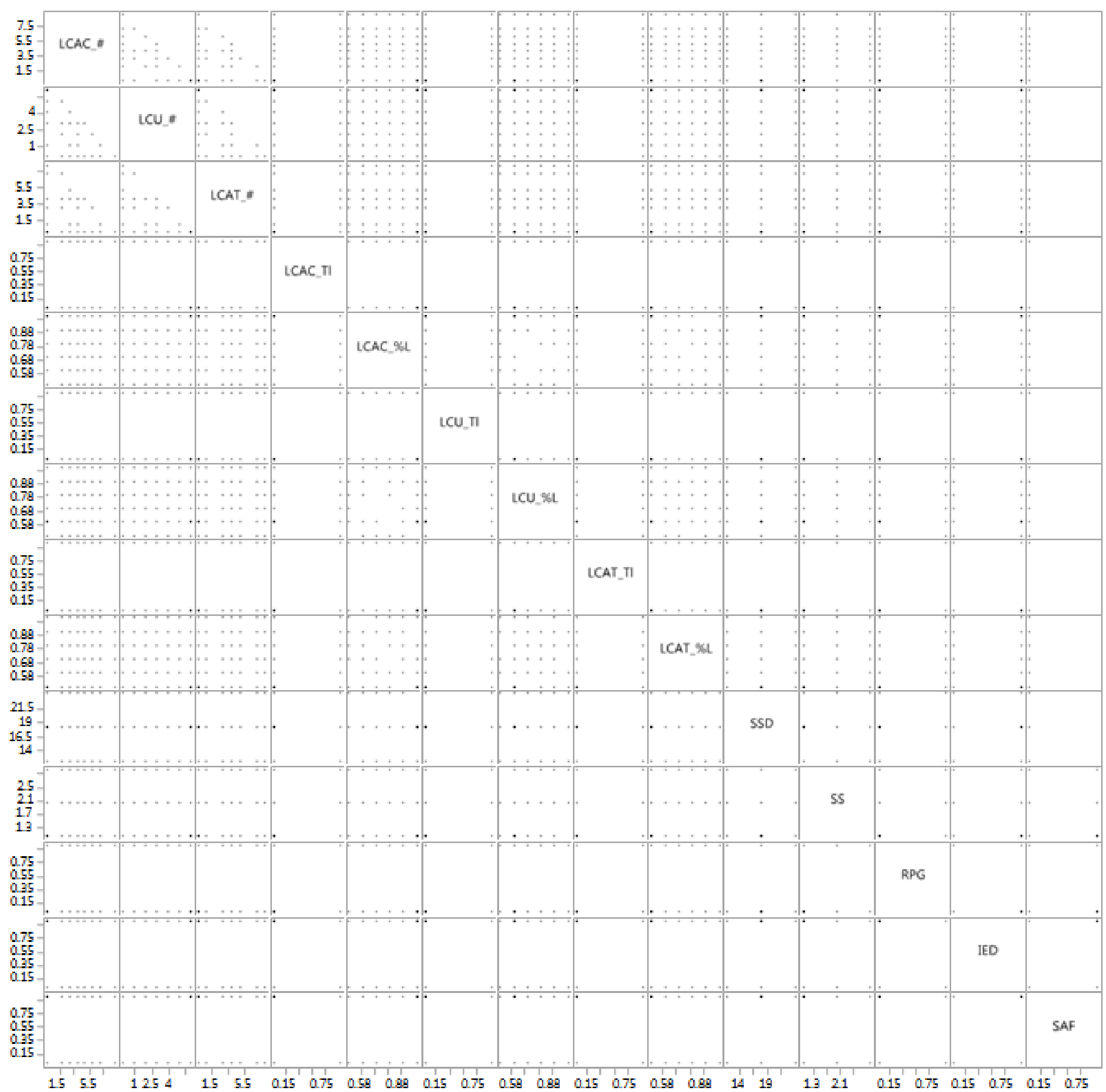


Figure 75. Scatterplot Matrix for the Resulting Design

C. THREE-DIMENSIONAL SCATTERPLOT MATRIX

Figure 76 shows a three-dimensional scatter plot matrix that was created in JMP Pro to evaluate in a three-dimensional space how well the shared design space was investigated for the number of LCACs, LCUs, and LCATs. Specifically, the three-dimensional scatterplot matrix shows the region of the design spacse that was explored for the number of LCACs, LCUs, and LCATs. Additionally, this plot illustrates the region of the design space that was not explored for the number of connectors due to the 27 feasible combinations of connectors that were considered for a three-ship ARG in this study.

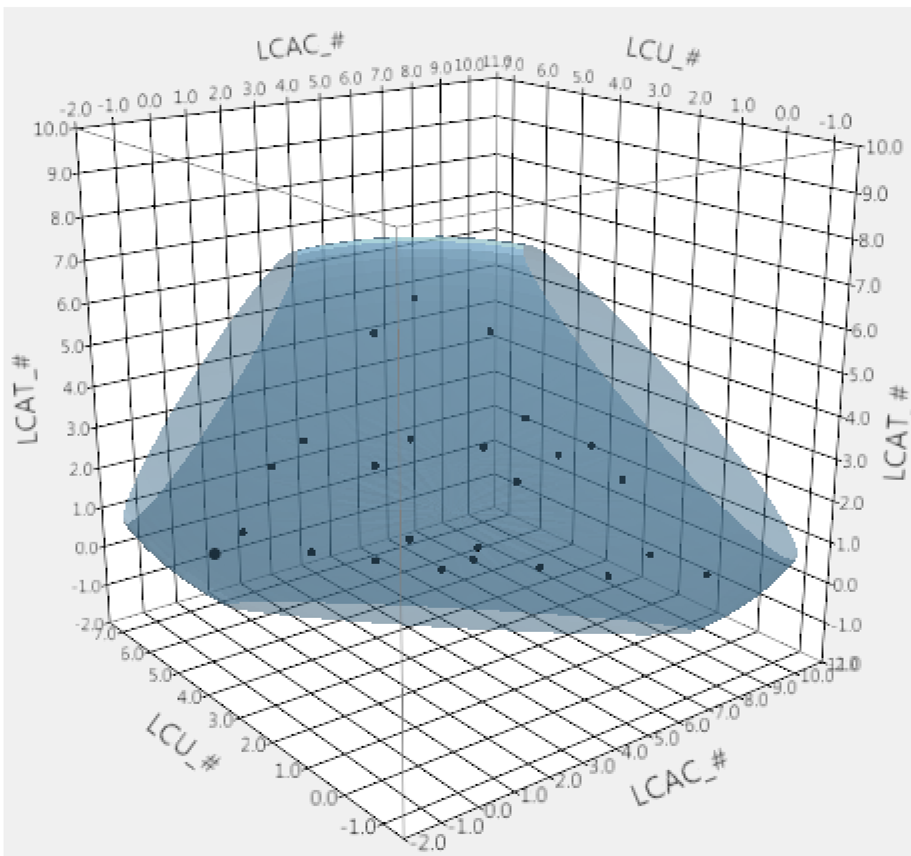


Figure 76. Three-Dimensional Scatterplot Matrix

D. PARTIAL VIEW OF THE DESIGN TABLE

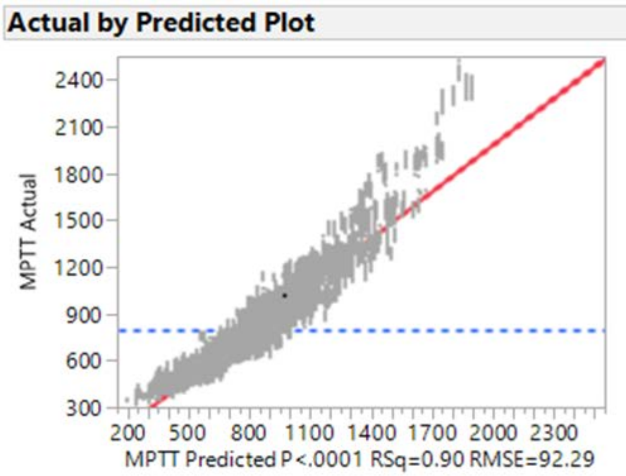
Figure 77 shows a portion of the design table that includes both the factors and responses of the seabase-to-shore operational model. Specifically, the partial view of the DOE design table shows the factors and responses for the first 23 simulation runs of the seabase-to-shore operational model. The complete version of the DOE design table consisted of 52,650 simulation runs for the seabase-to-shore operational model.

30/1 Cols 52650/1 Rows	LCAC_#	LCU_#	LCAT_#	LCAC_TI	LCAC_%L	LCU_TI	LCU_%L	LCAT_TI	LCAT_%L	SSD	SS	RPG	IED	SAF	MPTT	TFU	TLT	AS
1	0	6	0	1	0.5	0	0.7	0	0.9	24	2	1	1	1	1924	4154	117	7
2	0	6	0	1	0.9	0	0.7	0	0.6	18	3	1	1	1	1733	3768	110	6
3	0	6	0	1	0.7	1	0.6	0	0.9	12	2	0	1	1	1058	2458	109	7
4	0	6	0	1	0.9	1	0.7	0	0.7	18	2	0	1	1	1441	3084	103	7
5	0	6	0	1	0.7	0	0.5	0	0.6	18	2	1	0	0	1866	4393	50	7
6	0	6	0	1	1	0	0.7	0	0.8	12	3	1	0	0	1181	2485	39	5
7	0	6	0	1	0.6	1	0.5	0	0.7	24	2	0	0	0	2416	5690	0	8
8	0	6	0	1	0.9	1	0.7	0	1	18	1	0	0	0	1224	2704	13	8
9	0	6	0	1	0.5	0	0.9	0	0.8	18	1	1	0	1	944	2083	126	8
10	0	6	0	1	0.8	0	0.9	0	0.6	24	2	1	0	1	1416	3235	121	7
11	0	6	0	1	0.5	1	0.8	0	0.7	18	2	0	0	1	1249	2707	105	7
12	0	6	0	1	0.8	1	1	0	0.5	18	3	0	0	1	1232	2677	92	6
13	0	6	0	1	0.6	0	0.8	0	0.7	12	2	1	1	0	875	1823	38	7
14	0	6	0	1	0.8	0	0.9	0	1	12	1	1	1	0	654	1409	64	8
15	0	6	0	1	0.7	1	1	0	0.6	18	3	0	1	0	1209	2667	14	6
16	0	6	0	1	0.8	1	0.9	0	1	24	2	0	1	0	1377	3081	20	7
17	0	6	0	1	0.7	0	0.6	1	1	24	3	1	1	0	2354	5801	52	6
18	0	6	0	1	0.9	0	0.7	1	0.7	24	3	0	1	0	2242	4950	12	6
19	0	6	0	1	0.7	1	0.6	1	0.9	12	2	1	1	0	1019	2416	41	8
20	0	6	0	1	0.9	1	0.5	1	0.6	18	1	1	1	0	1614	3672	32	9
21	0	6	0	1	0.6	0	0.5	1	0.7	12	2	0	0	0	1287	2851	8	7
22	0	6	0	1	0.9	0	0.6	1	0.9	18	3	0	0	1	1774	4338	90	6
23	0	6	0	1	0.7	1	0.6	1	0.6	18	1	1	0	1	1296	3092	123	9
24	0	6	0	1	1	1	0.7	1	0.8	18	1	1	0	1	1261	2661	103	8
25	0	6	0	1	0.6	0	0.8	1	0.9	24	1	0	0	0	1436	3147	12	8
26	0	6	0	1	0.8	0	1	1	0.6	18	2	0	0	0	1063	2246	12	7
27	0	6	0	1	0.5	1	0.9	1	1	18	3	1	0	0	1247	2965	10	6

Figure 77. Partial View of the Generated Design Table

APPENDIX E. STATISTICAL ANALYSIS REGRESSION PLOTS

This appendix provides supporting analysis and figures for the statistical analysis regression plots discussed in Chapter IV.A.8. Figure 78-Figure 81 detail the linear regression for all four response variables. The following plots are included for each figure: Actual by Predicted Plot, Summary of Fit, analysis of variance (ANOVA), and Sorted Parameter Estimates.



Summary of Fit

RSquare	0.900143
RSquare Adj	0.900116
Root Mean Square Error	92.29015
Mean of Response	802.3497
Observations (or Sum Wgts)	52650

Analysis of Variance

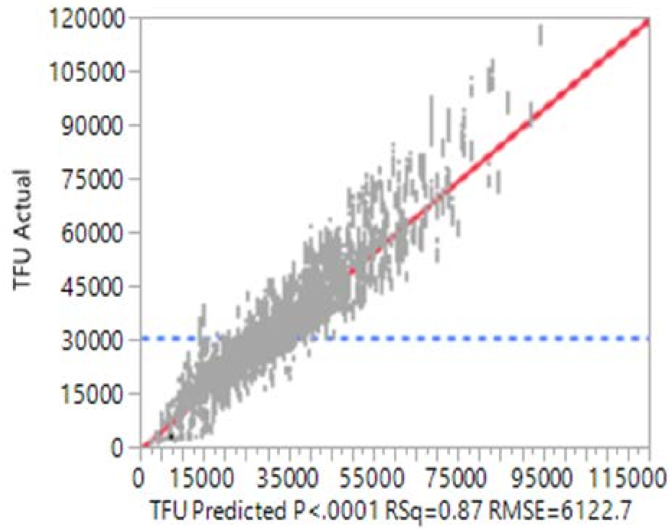
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	14	4041275074	288662505	33890.63
Error	52635	448317122	8517.4717	Prob > F
C. Total	52649	4489592197		<.0001*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
SSD	34.892905	0.096528	361.48	<.0001*
SS	118.91123	0.573502	207.34	<.0001*
(LCU_#-1.92593)*(SSD-18.0923)	6.3279142	0.052556	120.40	<.0001*
LCAC_#	-115.4065	0.964946	-119.6	<.0001*
(LCAC_#-3.11111)*(LCU_%L-0.75077)	123.29707	1.205791	102.25	<.0001*
LCAT_#	-96.94947	1.01207	-95.79	<.0001*
(LCAT_#-2.66667)*(LCU_%L-0.75077)	116.39837	1.239131	93.94	<.0001*
LCU_%L	-244.3589	2.659136	-91.89	<.0001*
LCAC_%L	-227.7015	2.659814	-85.61	<.0001*
LCAT_%L	-221.5238	2.637396	-83.99	<.0001*
(SS-2.01538)*(SS-2.01538)	52.744021	0.811855	64.97	<.0001*
(LCAT_#-2.66667)*(LCAT_%L-0.75077)	-63.32663	1.093746	-57.90	<.0001*
LCU_#	-47.01531	1.378617	-34.10	<.0001*
(LCAC_%L-0.75077)*(LCAC_%L-0.75077)	200.75285	18.17363	11.05	<.0001*

Figure 78. Regression Plots and Model Fit Parameters for MPTT

Actual by Predicted Plot



Summary of Fit

RSquare	0.871423
RSquare Adj	0.871403
Root Mean Square Error	6122.719
Mean of Response	30797.32
Observations (or Sum Wgts)	52650

Analysis of Variance

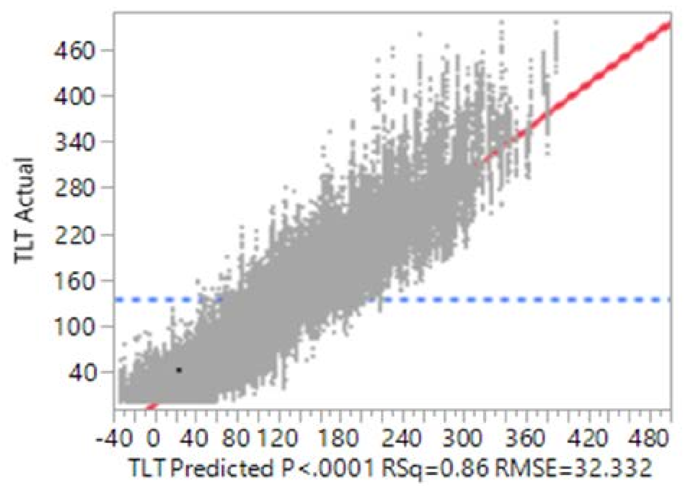
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	1.3374e+13	1.672e+12	44596.27
Error	52641	1.9734e+12	37487690	Prob > F
C. Total	52649	1.5348e+13		<.0001*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
LCAC_#	3382.9805	12.45177	271.69	<.0001*
SSD	1608.6138	6.352842	253.21	<.0001*
SS	7126.6361	37.81838	188.44	<.0001*
LCU_#	-2587.985	17.04741	-151.8	<.0001*
LCAC_%L	-26249.79	176.3347	-148.9	<.0001*
(LCAC_#-3.11111)*(LCAC_%L-0.75077)	-7949.141	71.28323	-111.5	<.0001*
(LCAC_#-3.11111)*(SSD-18.0923)	243.1859	2.556274	95.13	<.0001*
(LCU_#-1.92593)*(SS-2.01538)	-1278.753	20.81479	-61.43	<.0001*

Figure 79. Regression Plots and Model Fit Parameters for TFU

Actual by Predicted Plot



Summary of Fit

RSquare	0.861383
RSquare Adj	0.861344
Root Mean Square Error	32.33158
Mean of Response	135.7358
Observations (or Sum Wgts)	52650

Analysis of Variance

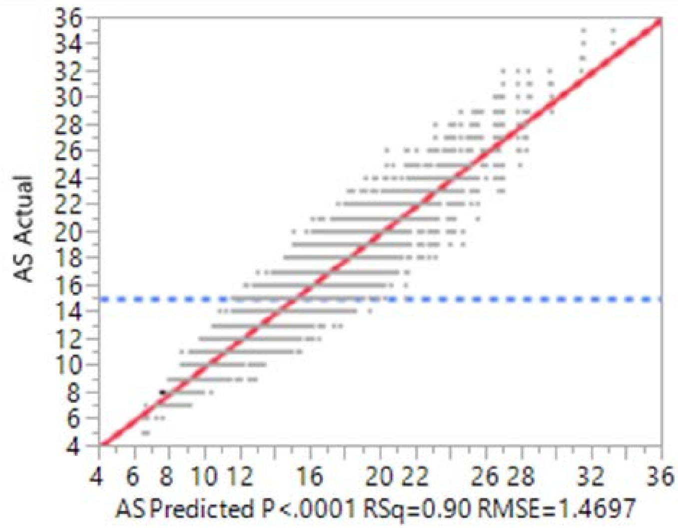
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	15	341901978	22793465	21805.03
Error	52634	55019940	1045.3308	Prob > F
C. Total	52649	396921919		<.0001*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
SAF	119.11538	0.294	405.15	<.0001*
(LCAT_#-2.66667)*(LCAT_%L-0.75077)	37.676776	0.384688	97.94	<.0001*
LCAT_%L	84.907246	0.953985	89.00	<.0001*
LCAC_#	29.721311	0.338854	87.71	<.0001*
(LCAC_#-3.11111)*(LCAC_%L-0.75077)	32.126843	0.372816	86.17	<.0001*
SSD	-2.815352	0.034205	-82.31	<.0001*
LCAT_#	29.201858	0.357191	81.75	<.0001*
(LCAC_#-3.11111)*(LCAC_#-3.11111)	1.6506597	0.021042	78.45	<.0001*
IED	19.828815	0.289347	68.53	<.0001*
LCAC_%L	61.666628	0.932555	66.13	<.0001*
(LCAT_#-2.66667)*(LCAT_#-2.66667)	1.567861	0.025225	62.15	<.0001*
LCU_#	17.630294	0.483333	36.48	<.0001*
(LCU_#-1.92593)*(SAF-0.50769)	-4.411377	0.156925	-28.11	<.0001*
(SSD-18.0923)*(IED-0.50769)	-0.708928	0.066588	-10.65	<.0001*
(LCAT_%L-0.75077)*(LCAT_%L-0.75077)	1.7807953	6.339261	0.28	0.7788

Figure 80. Regression Plots and Model Fit Parameters for TLT

Actual by Predicted Plot



Summary of Fit

RSquare	0.898565
RSquare Adj	0.89855
Root Mean Square Error	1.469668
Mean of Response	15.04914
Observations (or Sum Wgts)	52650

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	1007225.3	125903	58290.54
Error	52641	113700.6	2.159924	Prob > F
C. Total	52649	1120925.9		<.0001*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
LCAC_#	0.9440518	0.002989	315.86	<.0001*
LCU_#	-1.078555	0.004092	-263.6	<.0001*
SS	-2.356518	0.009078	-259.6	<.0001*
SSD	0.2116675	0.001525	138.81	<.0001*
LCAC_%L	-5.410241	0.042327	-127.8	<.0001*
(LCAC_#-3.11111)*(LCAC_%L-0.75077)	-1.827348	0.017009	-107.4	<.0001*
(LCAC_#-3.11111)*(SS-2.01538)	-0.380918	0.003653	-104.3	<.0001*
(LCU_#-1.92593)*(SSD-18.0923)	-0.047201	0.000834	-56.58	<.0001*

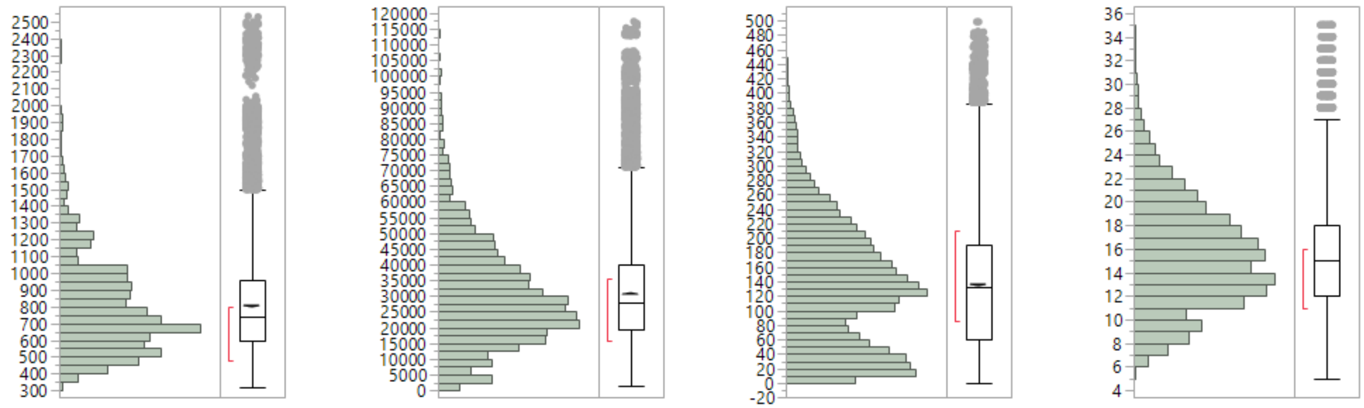
Figure 81. Regression Plots and Model Fit Parameters for AS

APPENDIX F. RESPONSE SURFACE DISTRIBUTIONS

This appendix provides supporting analysis and figures for the calculation of analysis limits based on response surface distributions discussed in Chapter IV.A.8. Figure 82 through Figure 83 detail the response surface distributions for both the response and predicted response variables.

Distributions

MPTT | **TFU** | **TLT** | **AS**



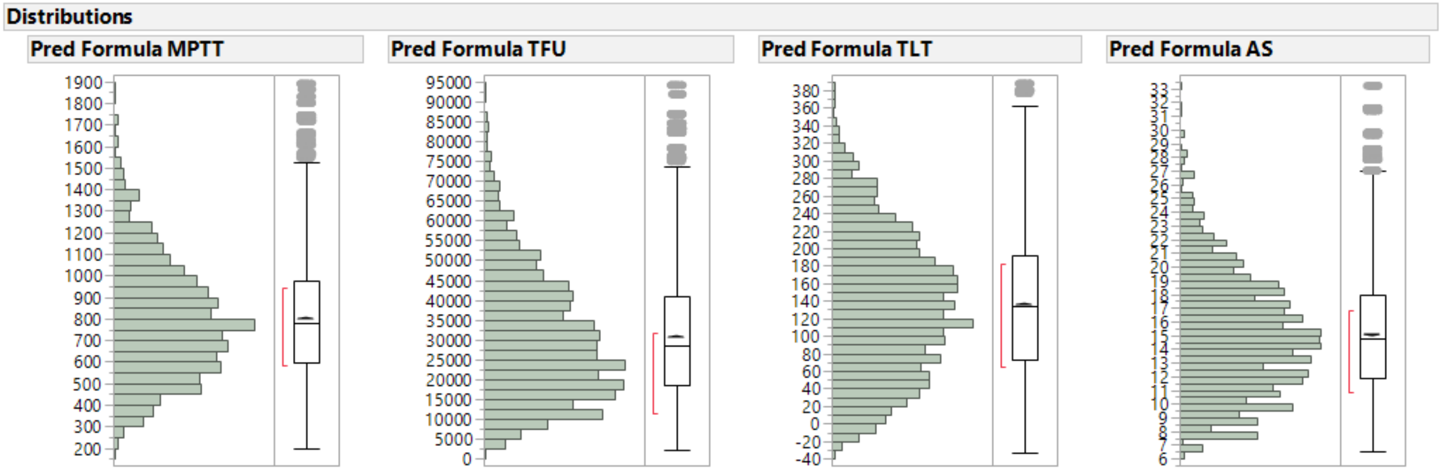
Quantiles

		MPTT	TFU	TLT	AS
100.0%	maximum	2532	117349	498	35
99.5%		1938	92388.96	397	30
97.5%		1527	72281.175	332	25
90.0%		1199	52988.9	249	21
75.0%	quartile	955	39994.5	191	18
50.0%	median	739	28048.5	132	15
25.0%	quartile	593	19282	61	12
10.0%		490.1	11722.1	24	9
2.5%		417	3210.275	9	7
0.5%		367.255	2065.255	0	6
0.0%	minimum	320	1317	0	5

Summary Statistics

	MPTT	TFU	TLT	AS
Mean	802.34967	30797.322	135.73582	15.049136
Std Dev	292.01717	17073.758	86.827536	4.6141678
Std Err Mean	1.2726506	74.409764	0.3784062	0.0201092
Upper 95% Mean	804.84407	30943.166	136.4775	15.08855
Lower 95% Mean	799.85526	30651.478	134.99414	15.009722
N	52650	52650	52650	52650

Figure 82. Response Distributions



Quantiles

Quantile		Pred Formula MPTT	Pred Formula TFU	Pred Formula TLT	Pred Formula AS
100.0%	maximum	1890.3224186	94124.458047	387.73775524	33.19900545
99.5%		1717.1185216	82251.757252	343.1325745	28.263455822
97.5%		1410.7201181	68574.066596	299.11038374	24.531337429
90.0%		1171.3628272	52492.592376	242.55769839	20.682515783
75.0%	quartile	975.10811517	40784.611705	191.39326954	17.928653289
50.0%	median	779.52947321	28420.056782	133.37488294	14.773355396
25.0%	quartile	597.72713732	18642.277762	72.470346274	11.881182873
10.0%		466.4196068	11834.820455	30.229038559	9.6410716808
2.5%		345.49639004	7153.9349262	-3.959695001	7.6927709207
0.5%		272.29117097	4129.8845321	-19.85343484	6.5762983673
0.0%	minimum	194.85439991	2364.8973774	-33.21608029	6.4875856707

Summary Statistics

	Pred Formula MPTT	Pred Formula TFU	Pred Formula TLT	Pred Formula AS
Mean	802.34967	30797.322	135.73582	15.049136
Std Dev	277.05382	15938.357	80.585284	4.373894
Std Err Mean	1.2074383	69.461531	0.3512017	0.019062
Upper 95% Mean	804.71626	30933.467	136.42418	15.086498
Lower 95% Mean	799.98308	30661.176	135.04746	15.011774
N	52650	52650	52650	52650

Figure 83. Predicted Formula Response Distributions

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APPENDIX G. STATISTICAL ANALYSIS PREDICTION PROFILER PLOTS

This appendix provides supporting analysis and figures for the statistical analysis conducted using the prediction profiler discussed in Chapter IV.A.8. Figure 84 details the response surface prediction profiler plot when the maximize desirability function was enabled. The limits for the statistical analysis were entered as desirability settings identified to the far right of the plot. Maximized desirability values for all factors are identified in the last row of the plot.

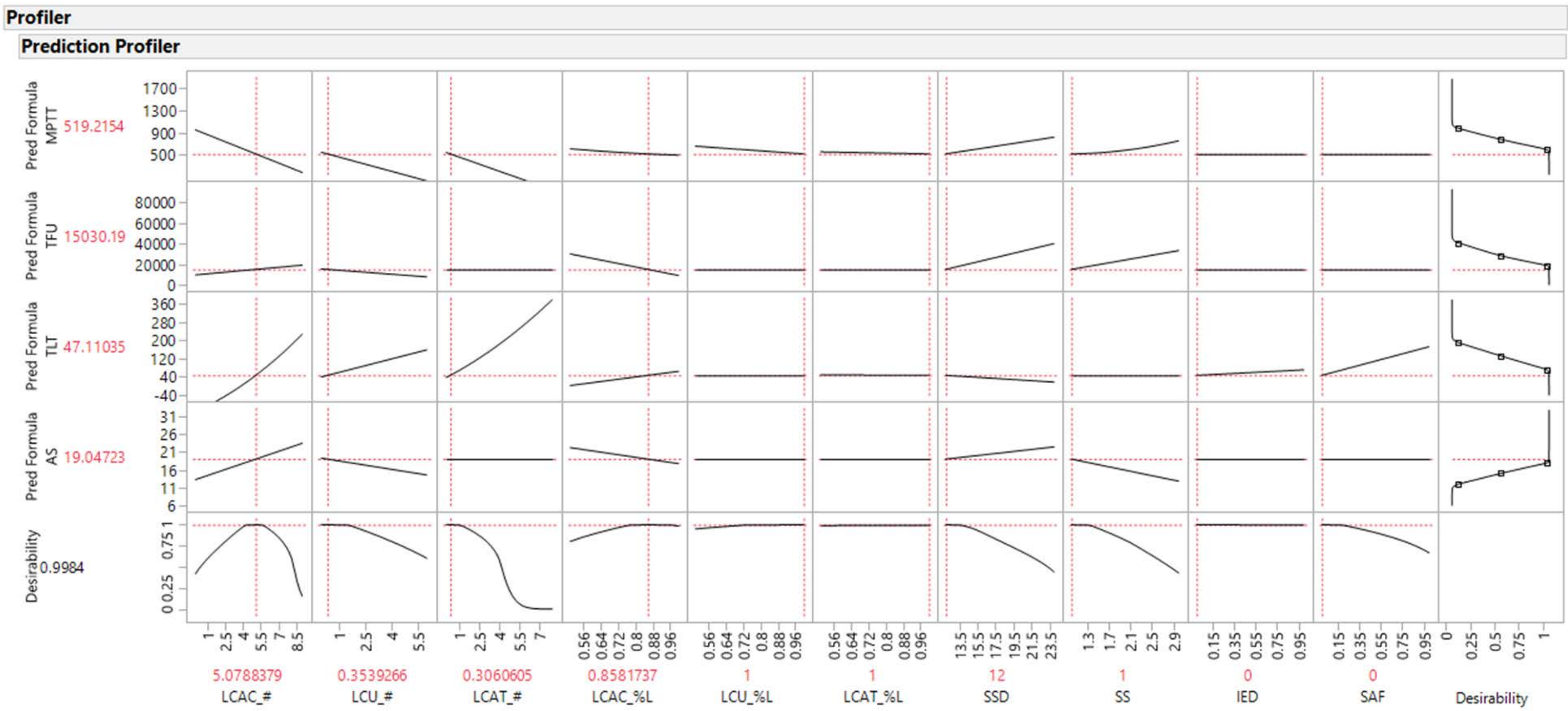

Figure 84. Response Surface Profiler Plot

APPENDIX H. STATISTICAL ANALYSIS CONTOUR PLOTS

This appendix provides supporting analysis and figures for the statistical analysis conducted using the contour plots discussed in Chapter IV.A.8. Figure 85 through Figure 165 detail the contour plots for all 27 connector scenarios that are a realizable configuration in the well-decks of a three-ship Amphibious Readiness Group (ARG). For each scenario, the first plot details the solution space when the mission payload transfer time (MPTT) and total fuel used (TFU) limits are applied. The next contour plot details the solution space when the total loiter time (TLT) and average speed (AS) limits are applied in addition to MPTT and TFU. The third contour plot details the limiting factor where for the given connector scenario, the solution space no longer exists. Each contour plot has a graphic showing the scenario number and the connectors that make up that scenario.

Scenario #1		
LCU	LCAC	LCAT
6	0	0

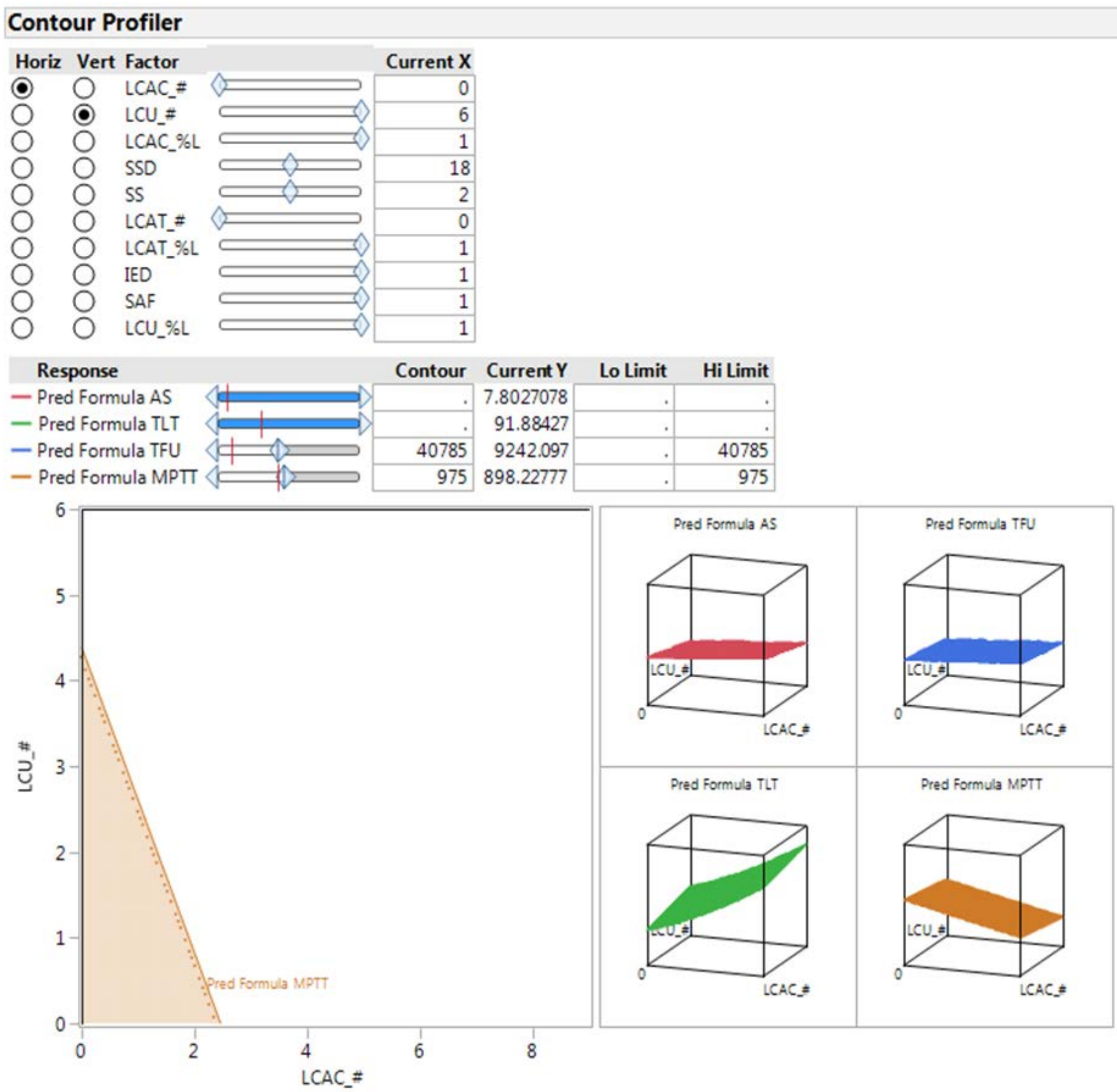

Figure 85. Scenario 1 Solution Space Contour Plot

Scenario #1		
LCU	LCAC	LCAT
6	0	0

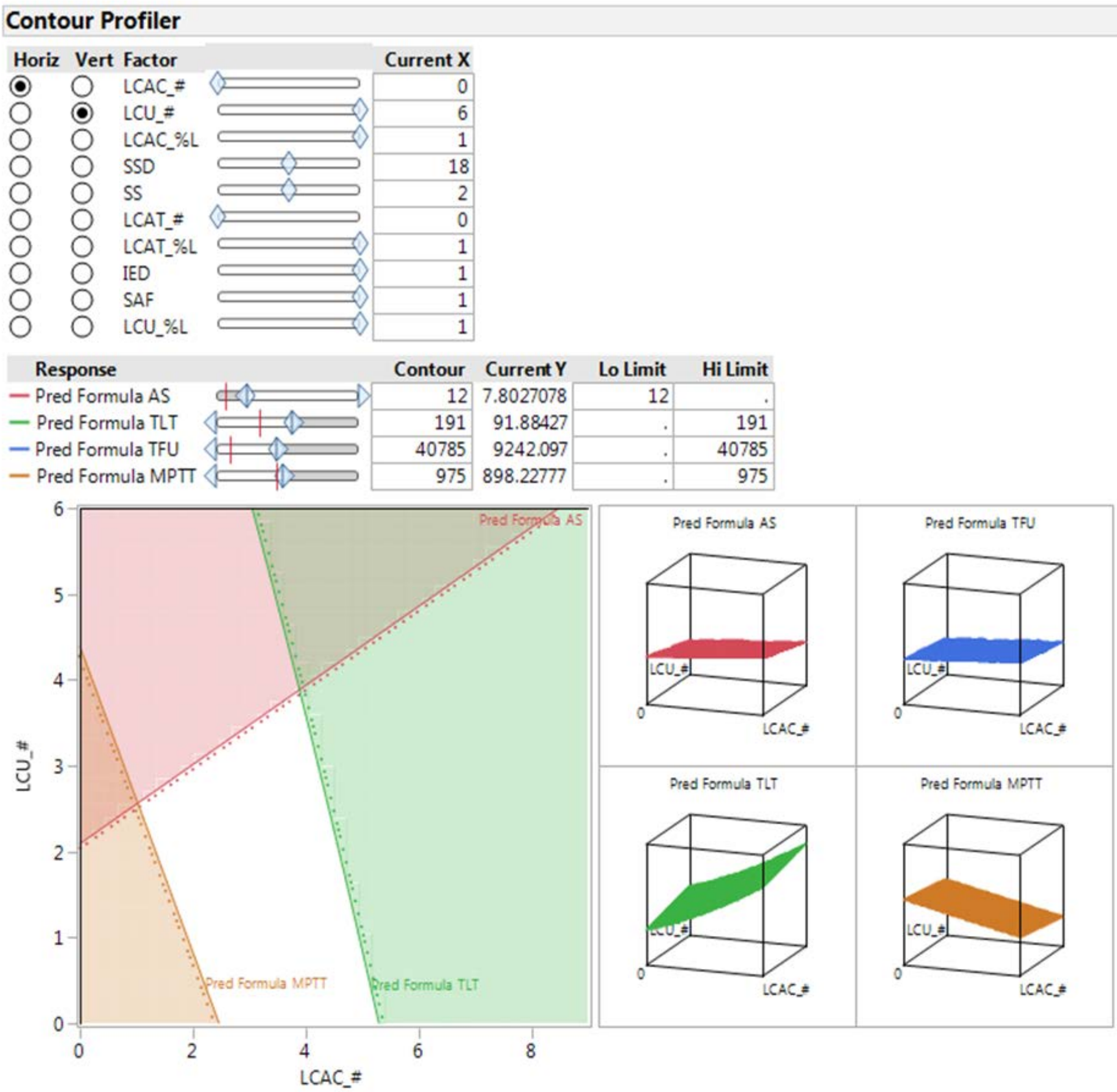

Figure 86. Scenario 1 Solution Space with TLT and AS Contour Plot

Scenario #1		
LCU	LCAC	LCAT
6	0	0

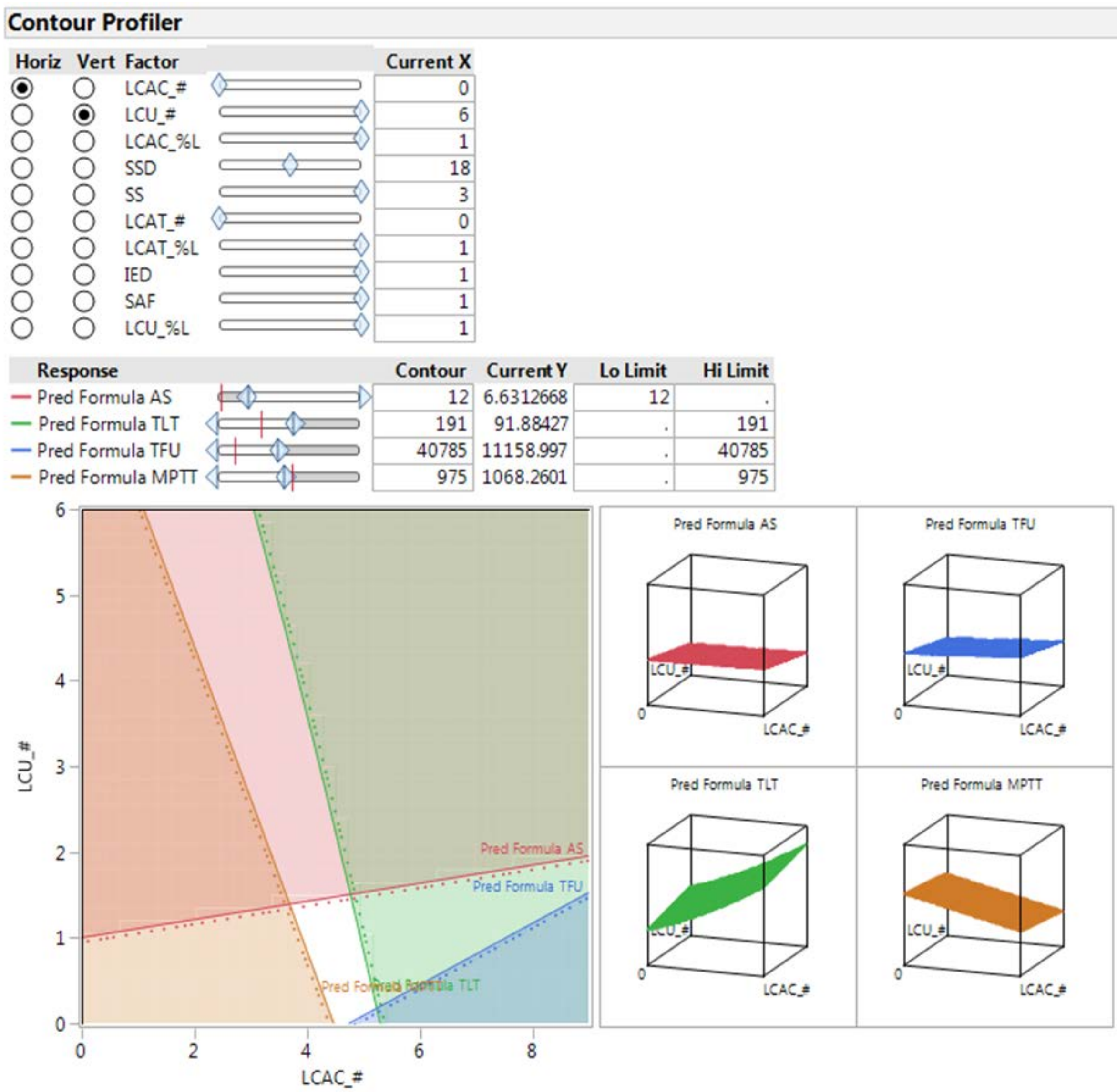

Figure 87. Scenario 1 Limiting Response Contour Plot

Scenario #2		
LCU	LCAC	LCAT
3	4	0

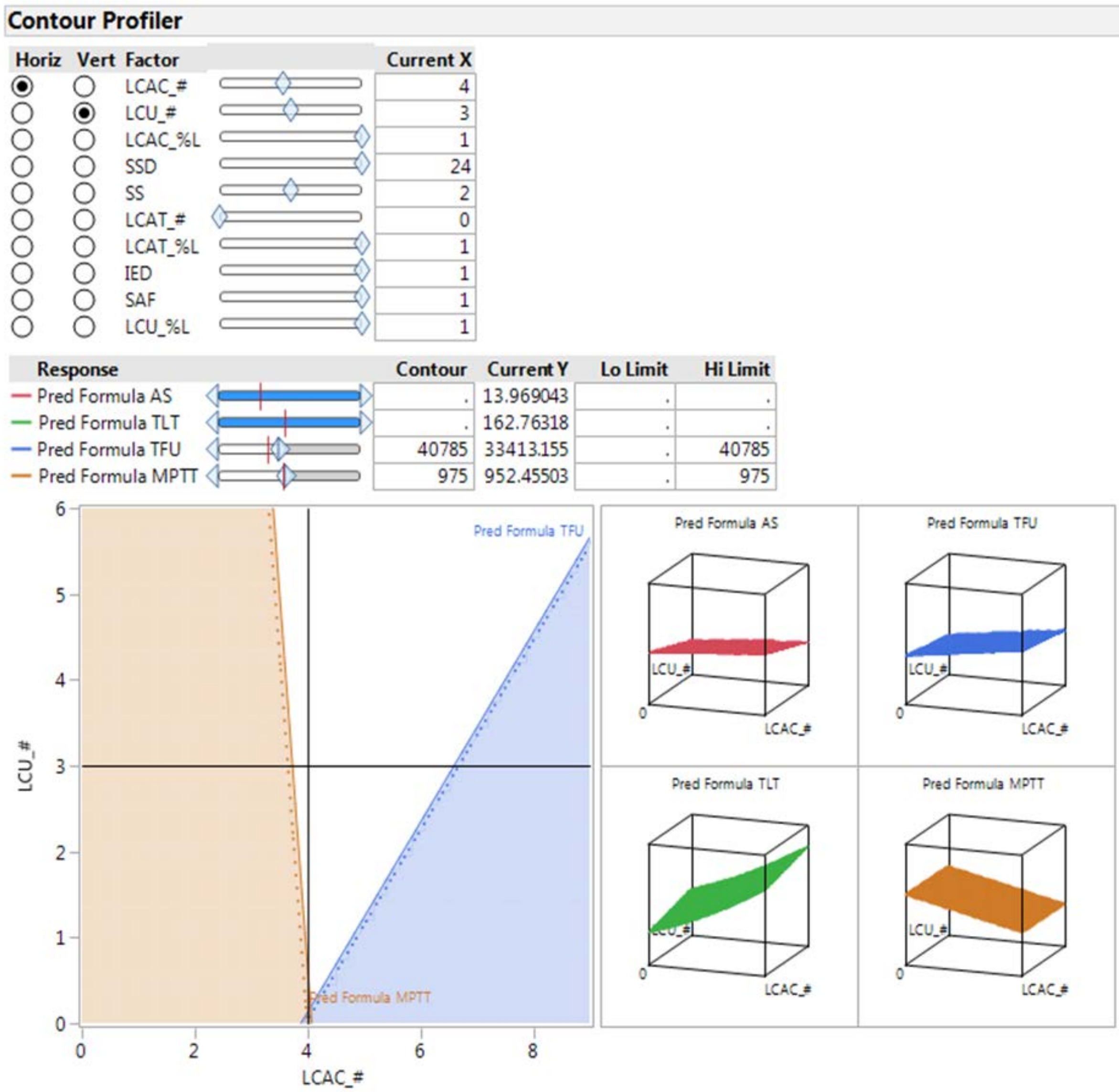

Figure 88. Scenario 2 Solution Space Contour Plot

Scenario #2		
LCU	LCAC	LCAT
3	4	0

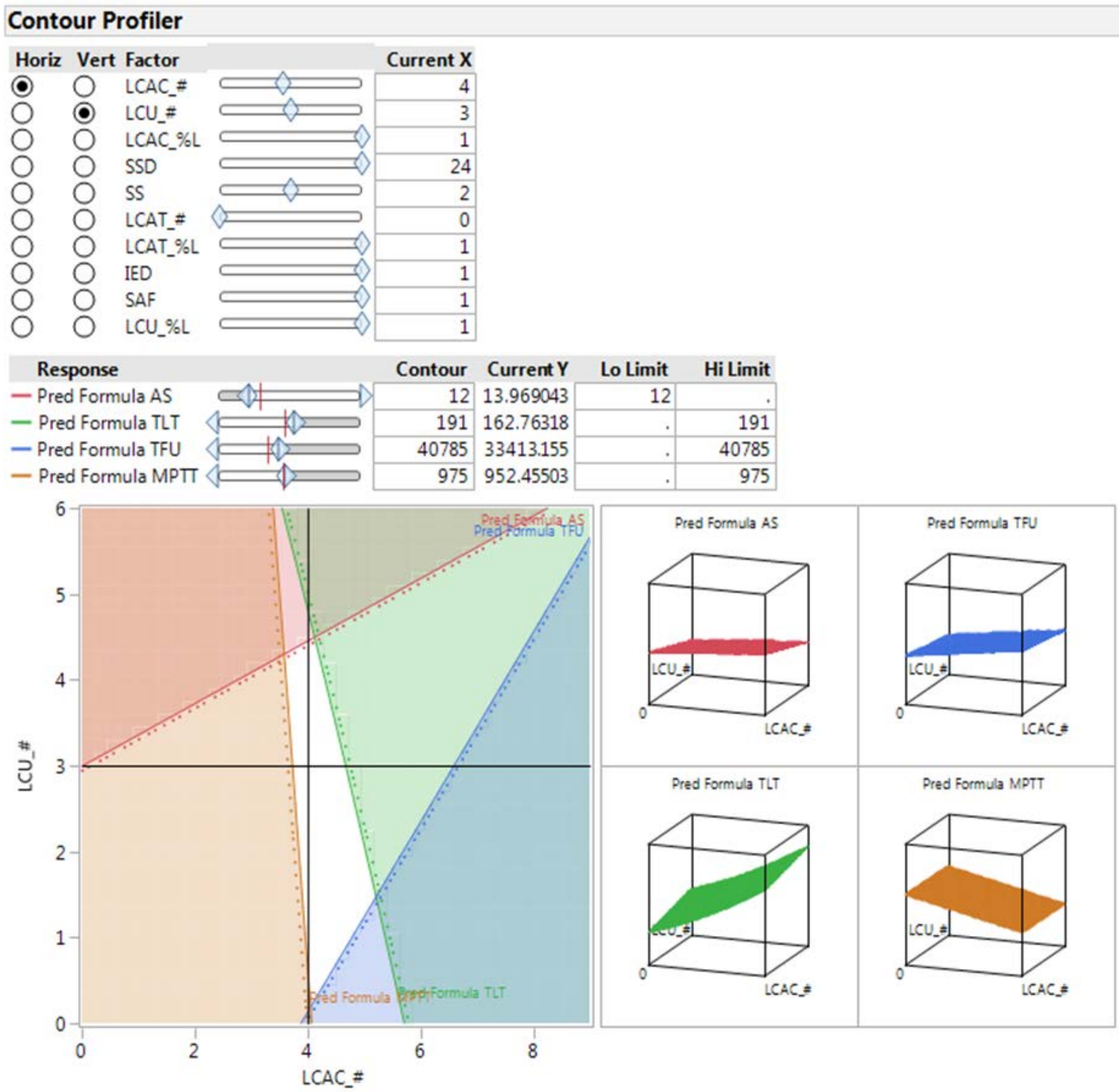

Figure 89. Scenario 2 Solution Space with TLT and AS Contour Plot

Scenario #2		
LCU	LCAC	LCAT
3	4	0

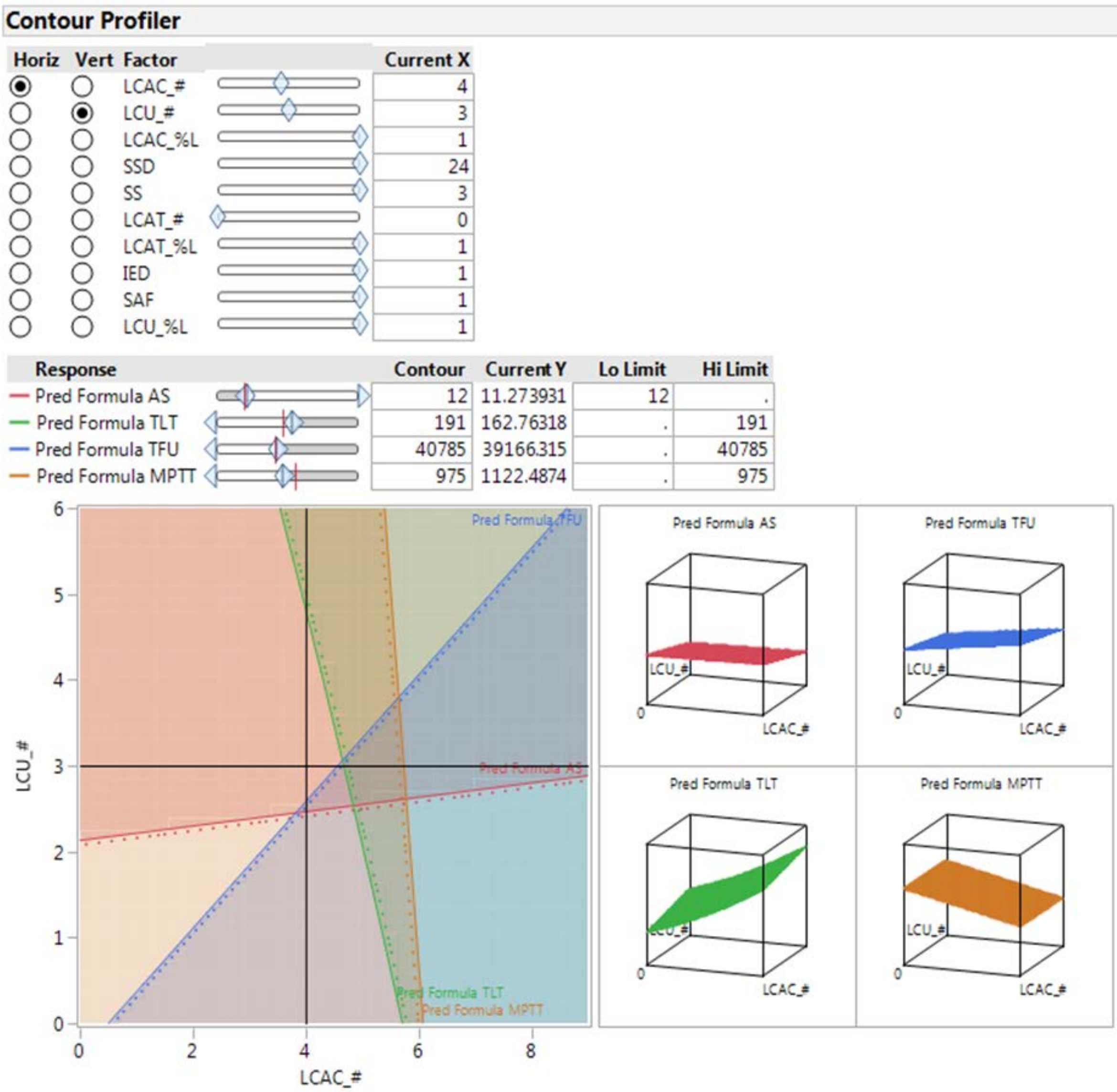

Figure 90. Scenario 2 Limiting Response Contour Plot

Scenario #3		
LCU	LCAC	LCAT
3	0	4

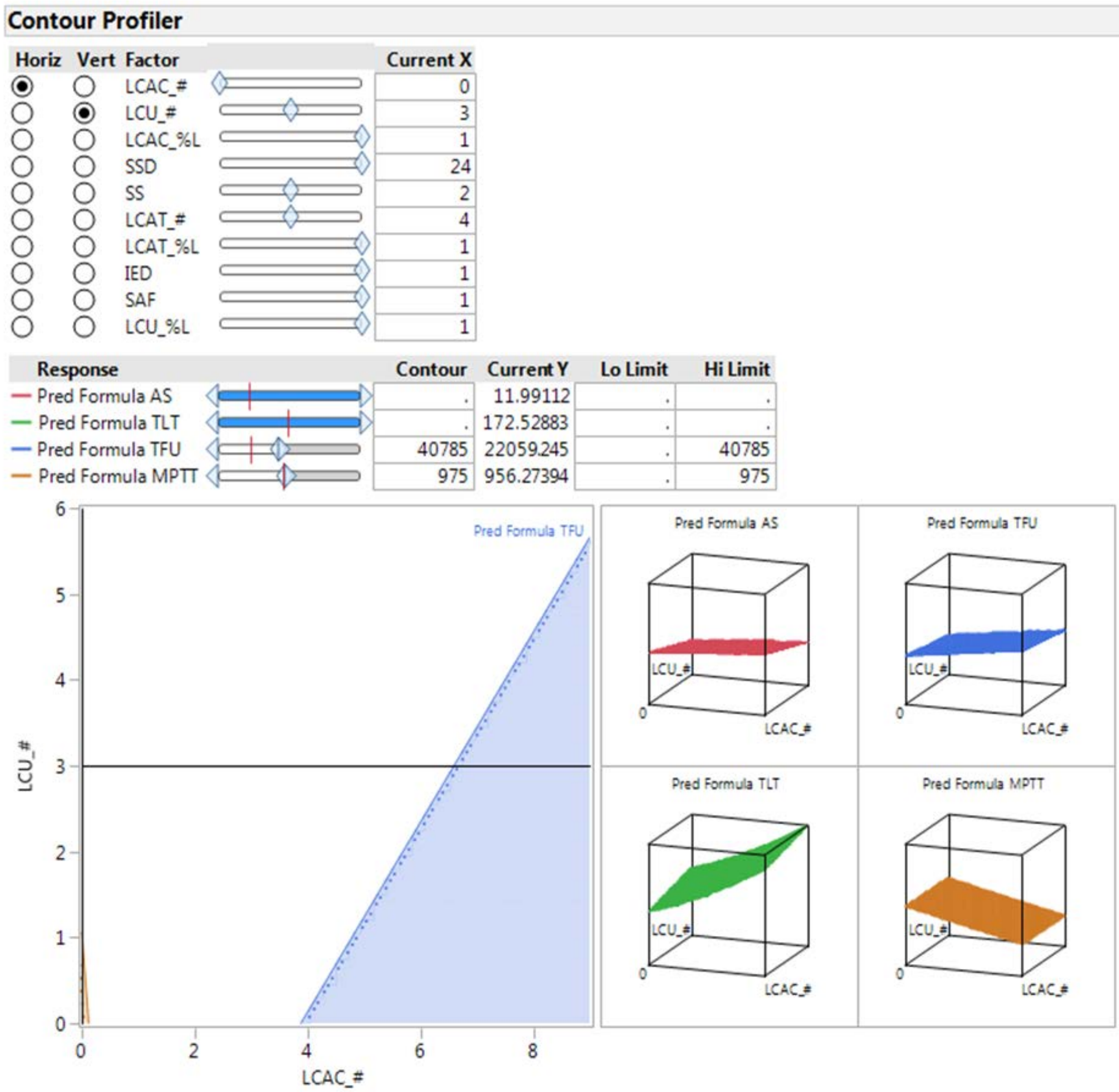

Figure 91. Scenario 3 Solution Space Contour Plot

Scenario #3		
LCU	LCAC	LCAT
3	0	4

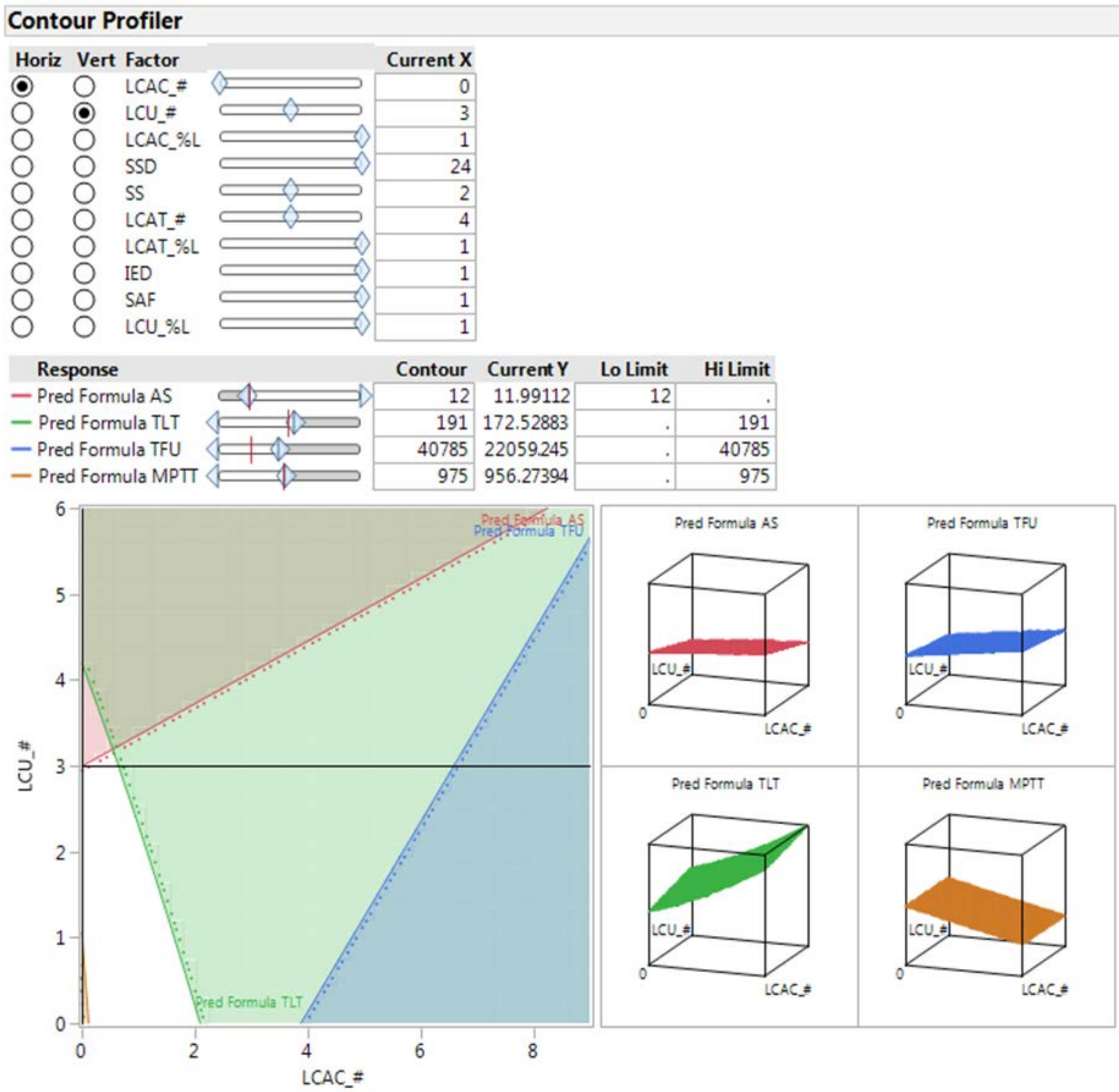

Figure 92. Scenario 3 Solution Space with TLT and AS Contour Plot

Scenario #3		
LCU	LCAC	LCAT
3	0	4

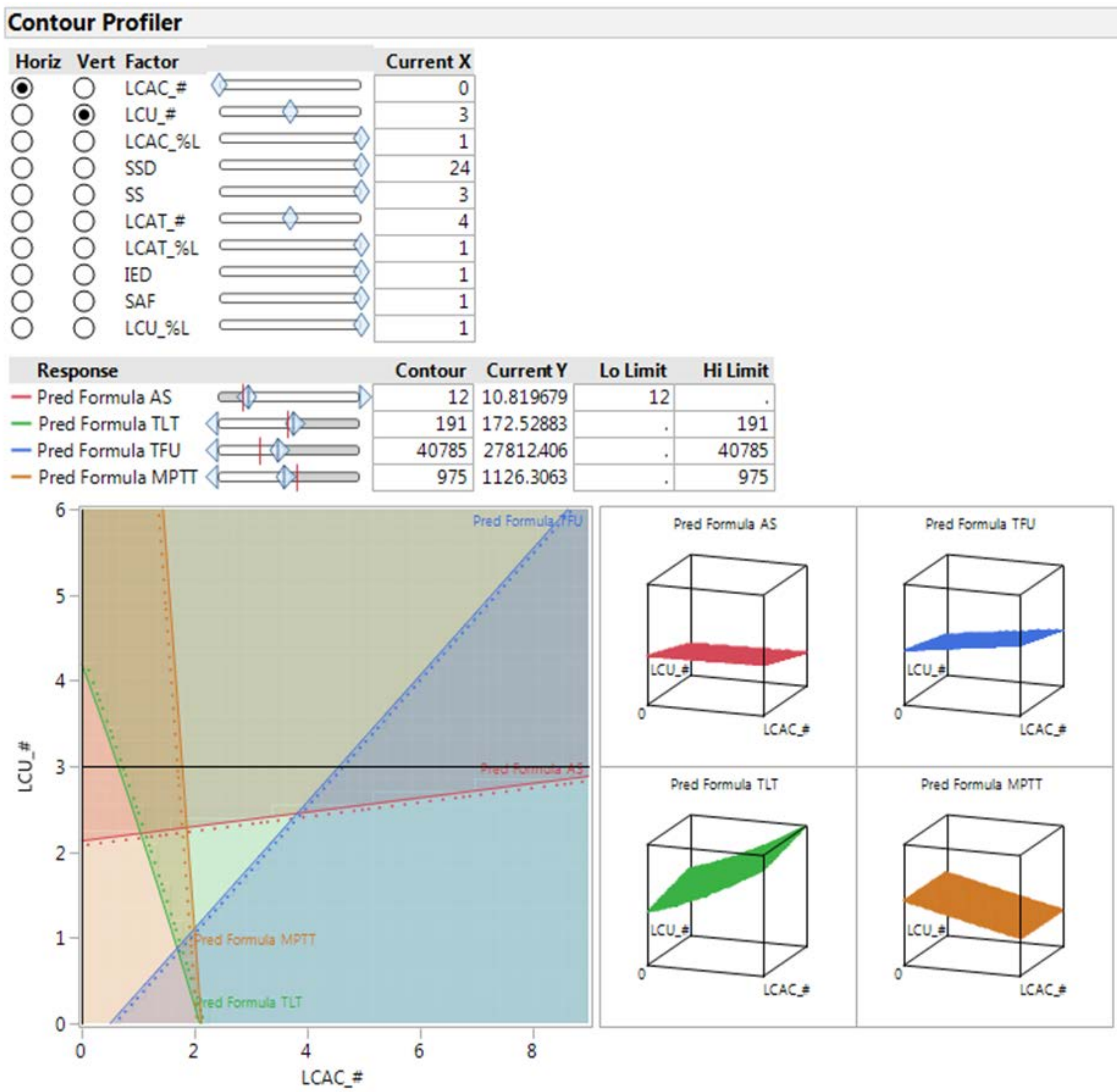

Figure 93. Scenario 3 Limiting Response Contour Plot

Scenario #4		
LCU	LCAC	LCAT
5	2	0

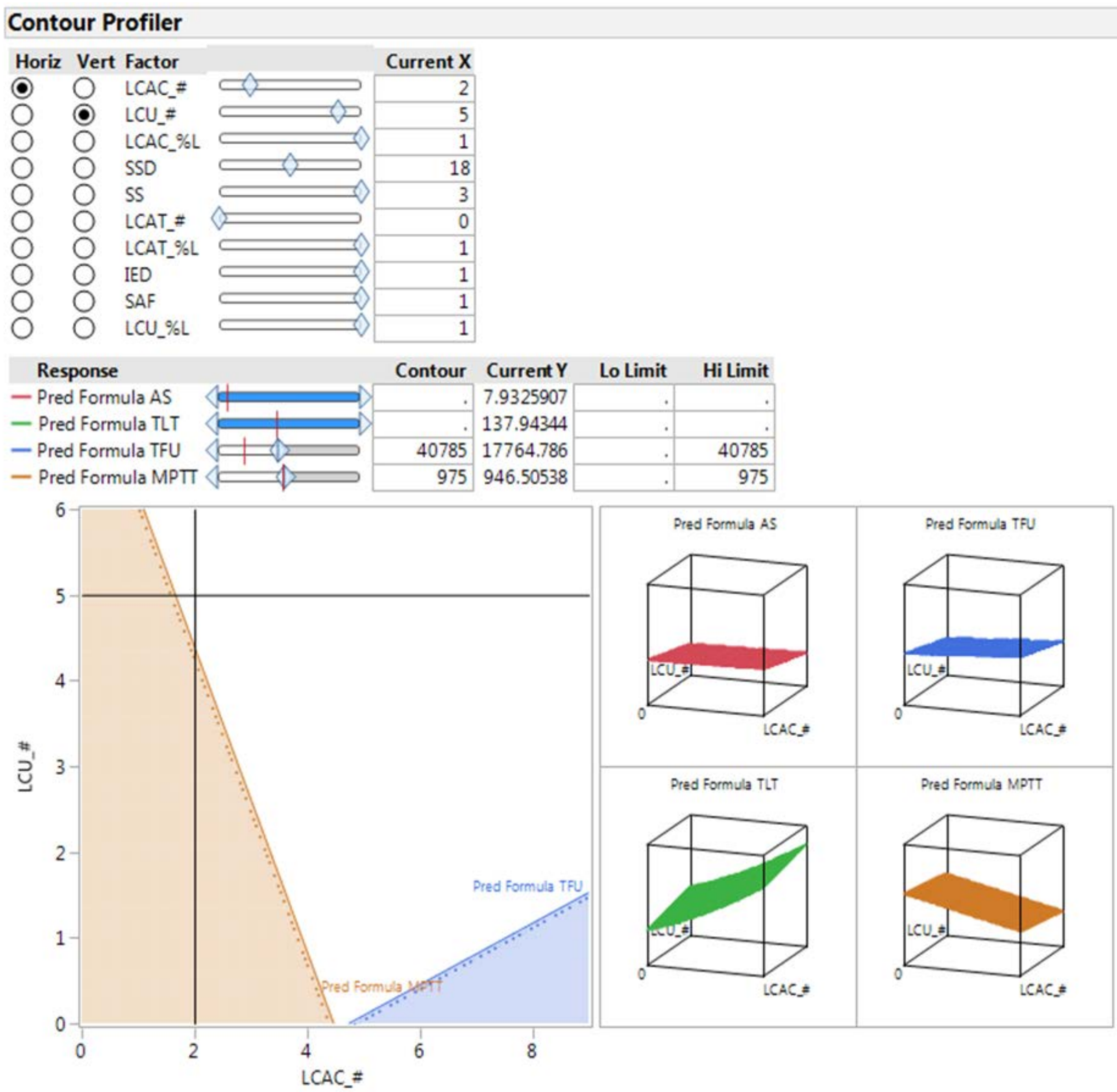

Figure 94. Scenario 4 Solution Space Contour Plot

Scenario #4		
LCU	**LCAC**	**LCAT**
5	2	0

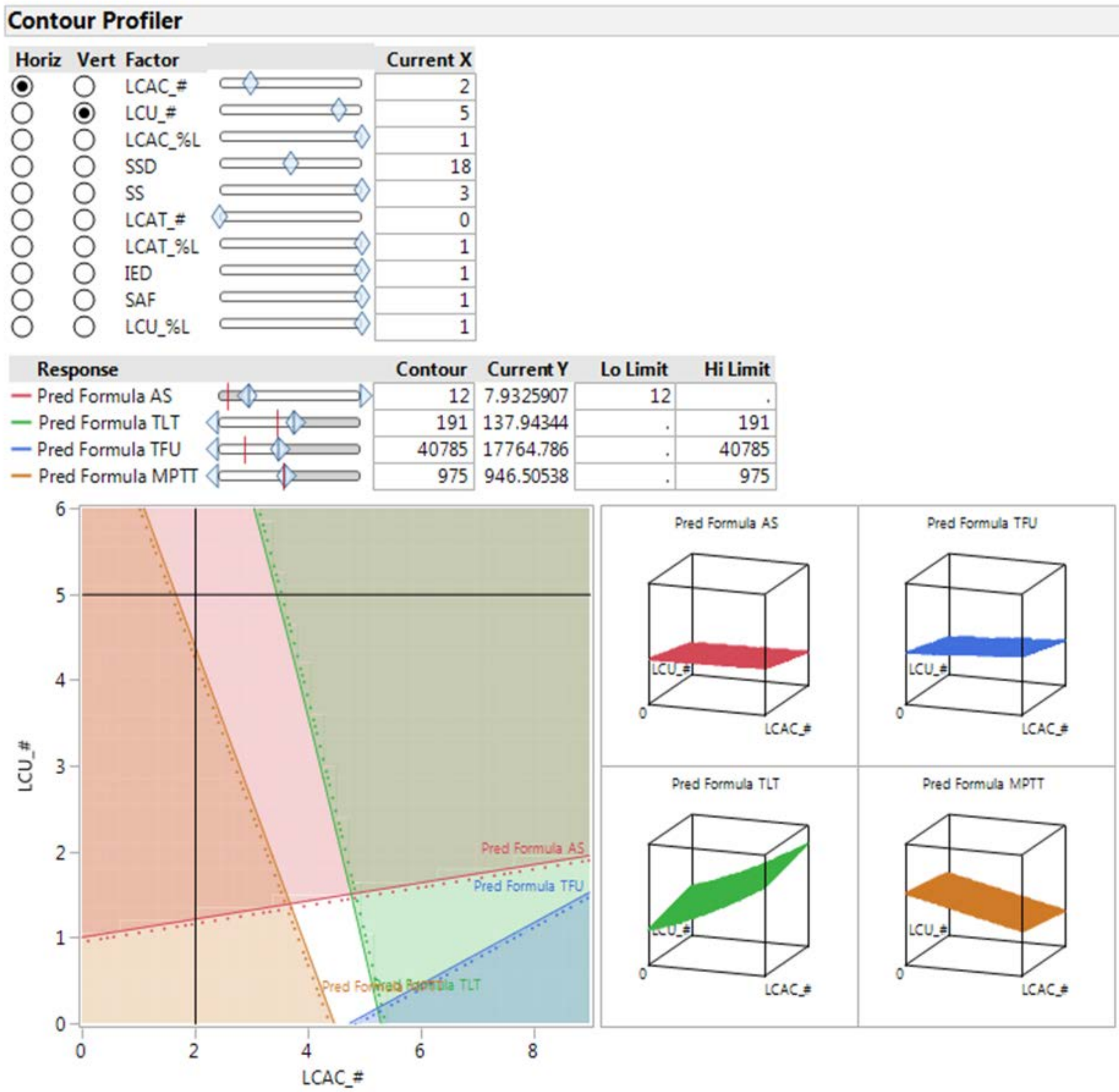

Figure 95. Scenario 4 Solution Space with TLT and AS Contour Plot

Scenario #4		
LCU	LCAC	LCAT
5	2	0

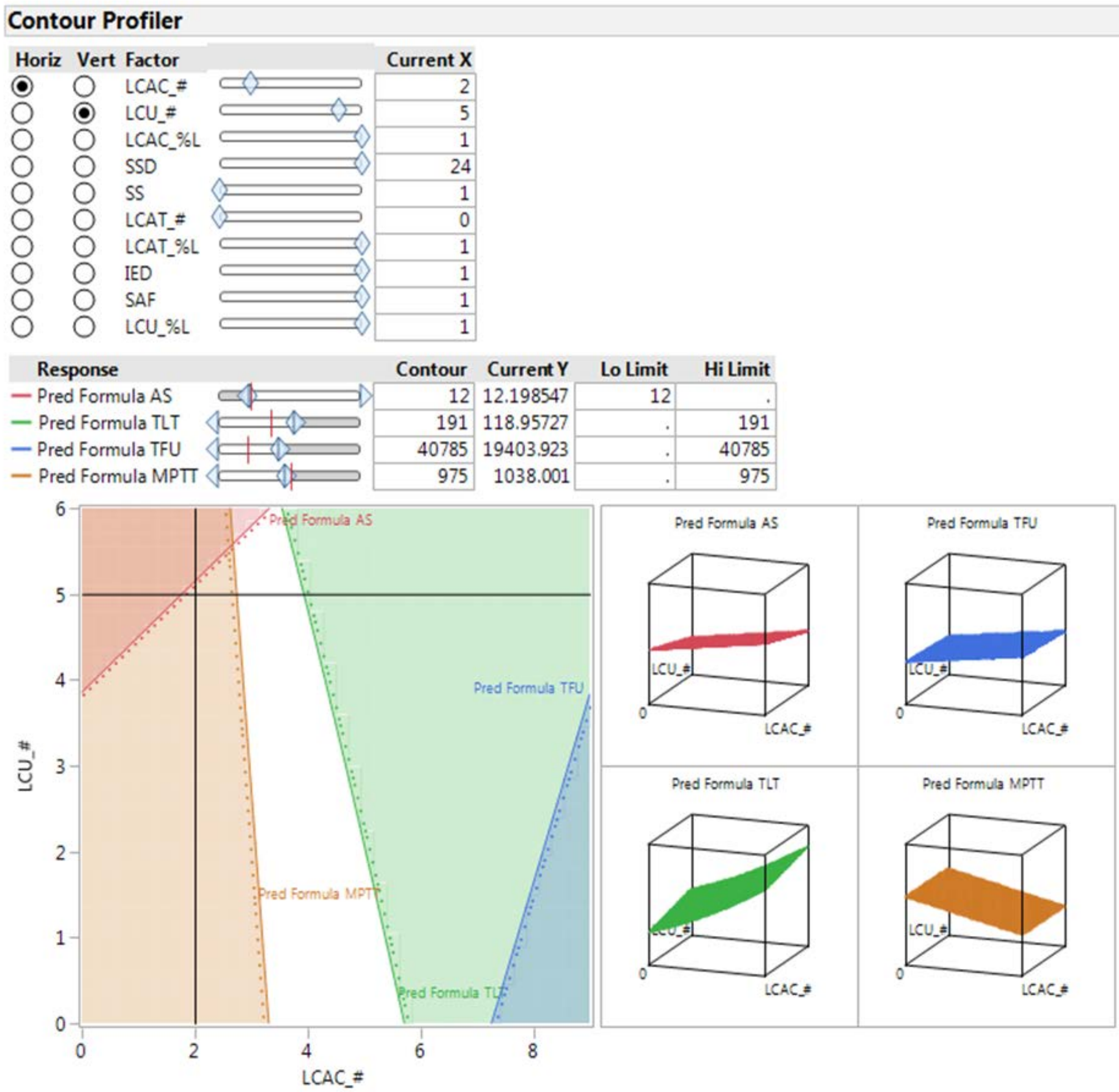

Figure 96. Scenario 4 Limiting Response Contour Plot

Scenario #5		
LCU	LCAC	LCAT
2	6	0

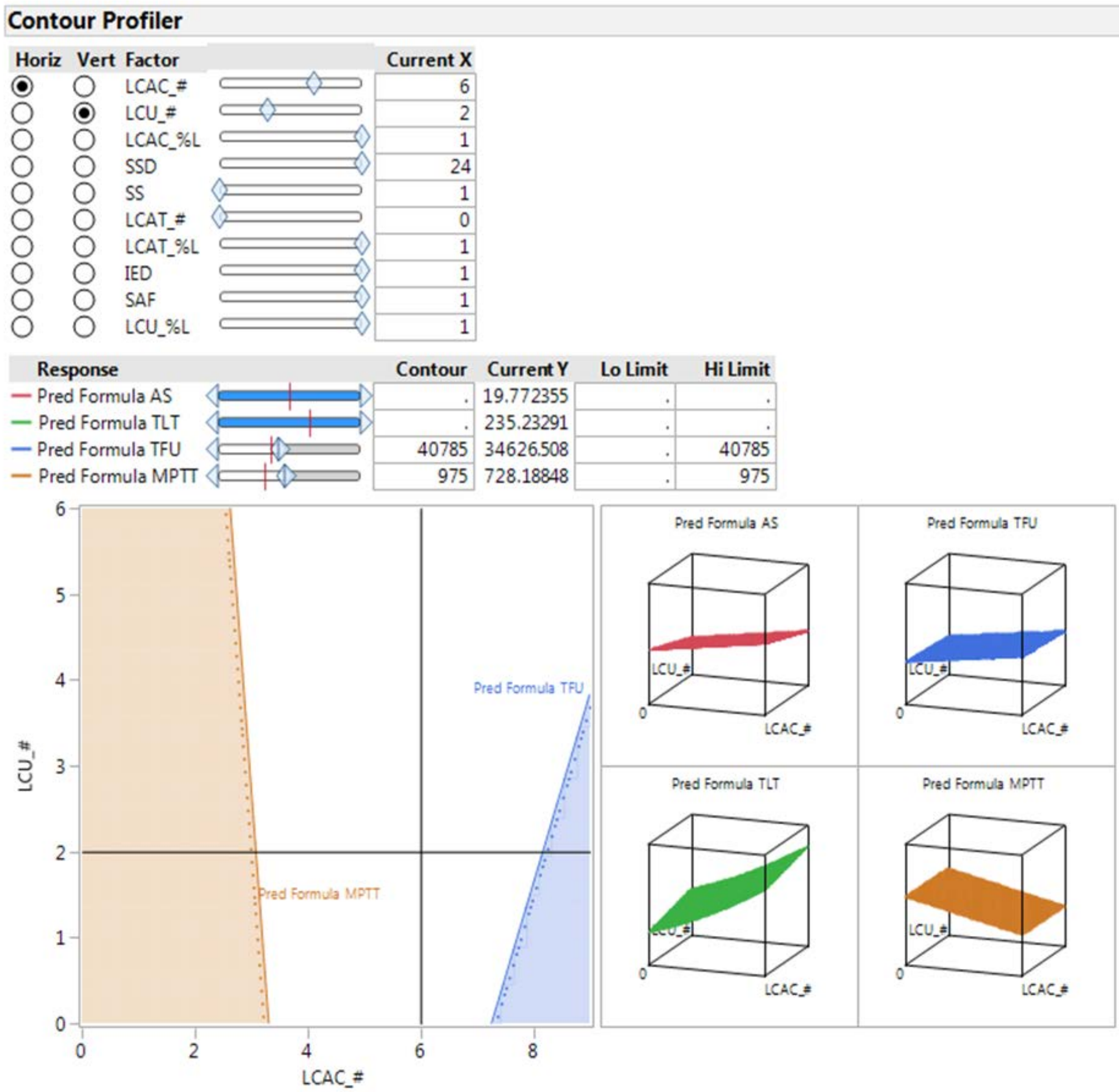

Figure 97. Scenario 5 Solution Space Contour Plot

Scenario #5		
LCU	**LCAC**	**LCAT**
2	6	0

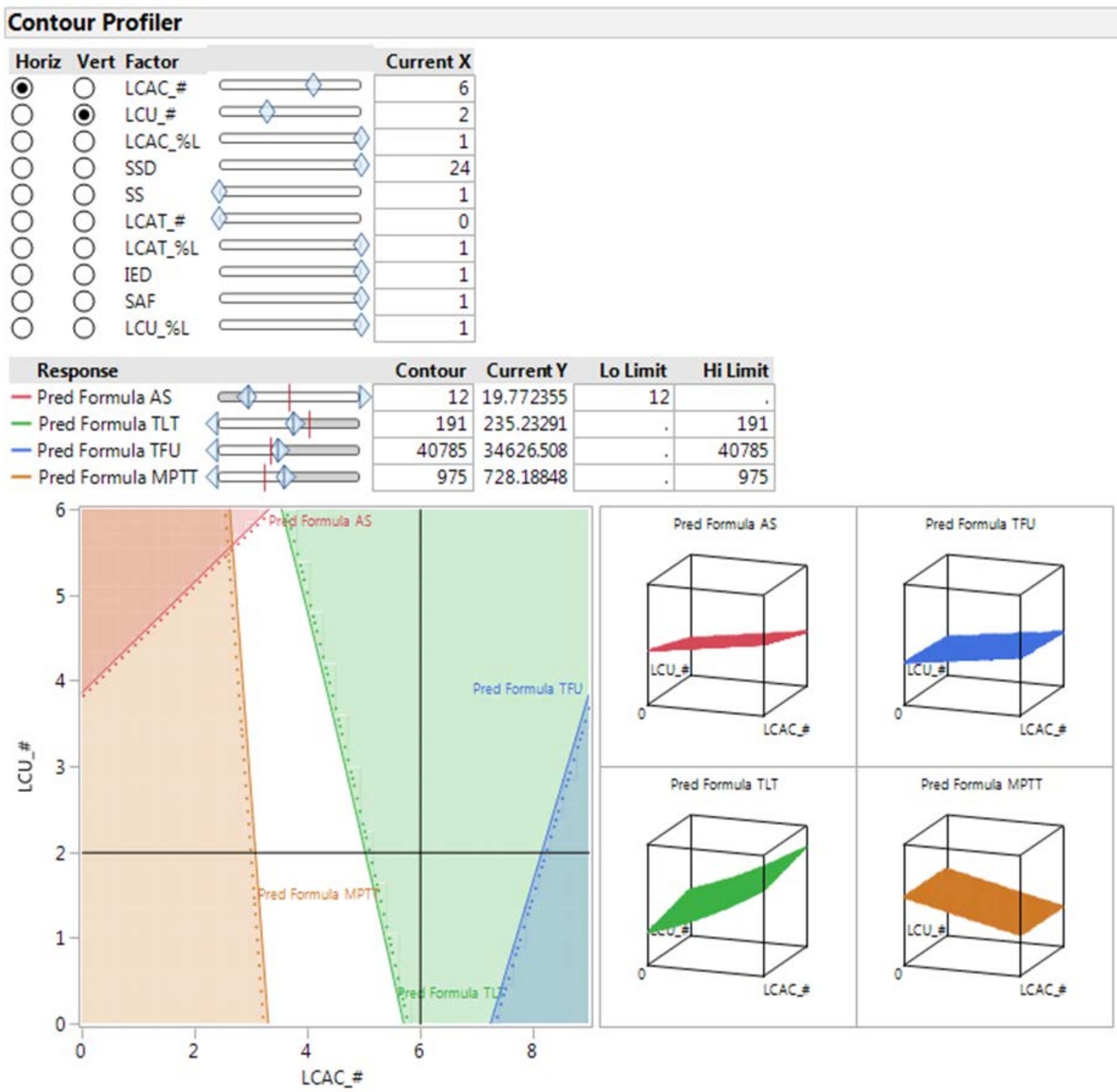

Figure 98. Scenario 5 Solution Space with TLT and AS Contour Plot

Scenario #5		
LCU	LCAC	LCAT
2	6	0

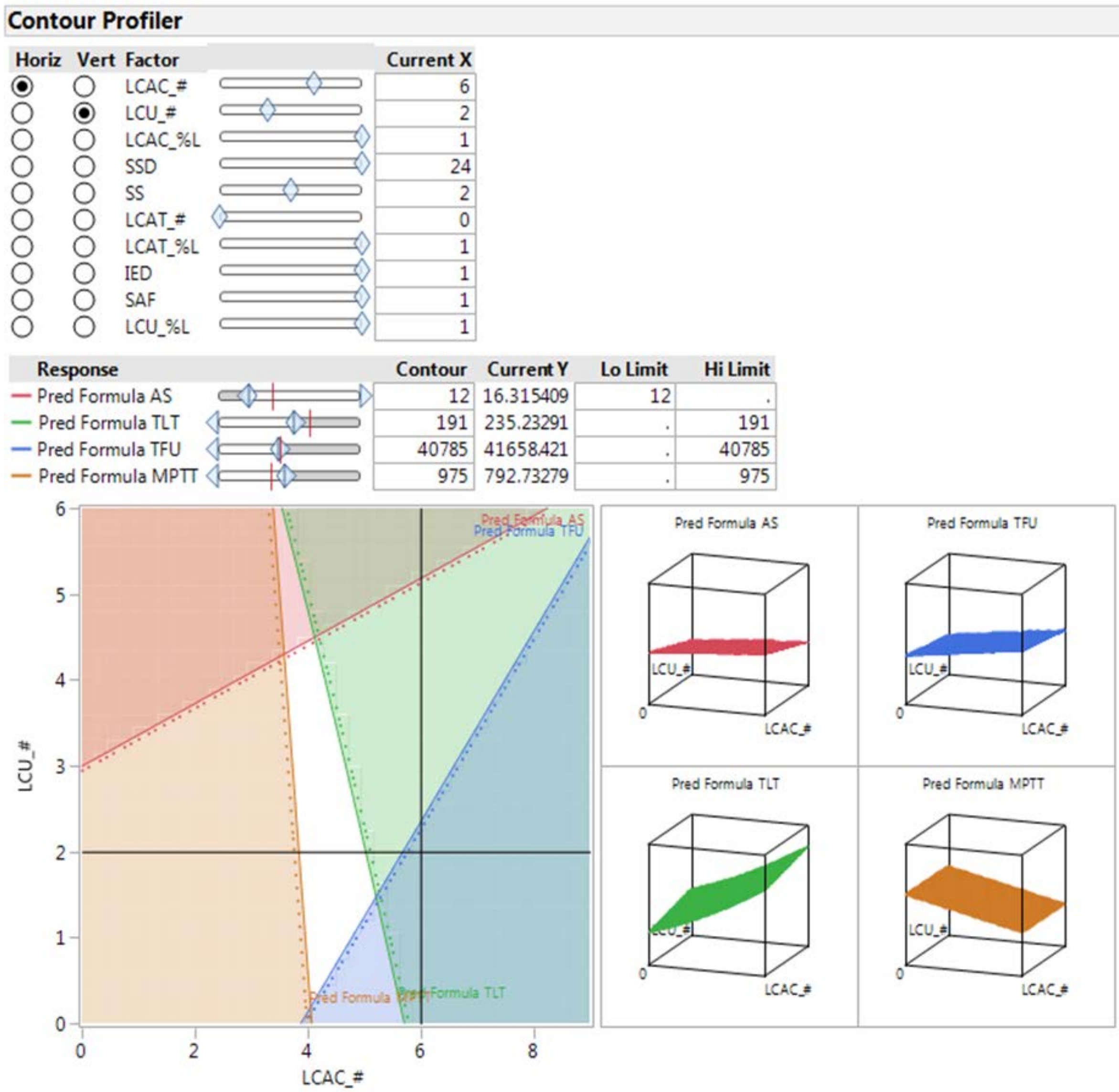

Figure 99. Scenario 5 Limiting Response Contour Plot

Scenario #6		
LCU	LCAC	LCAT
2	2	4

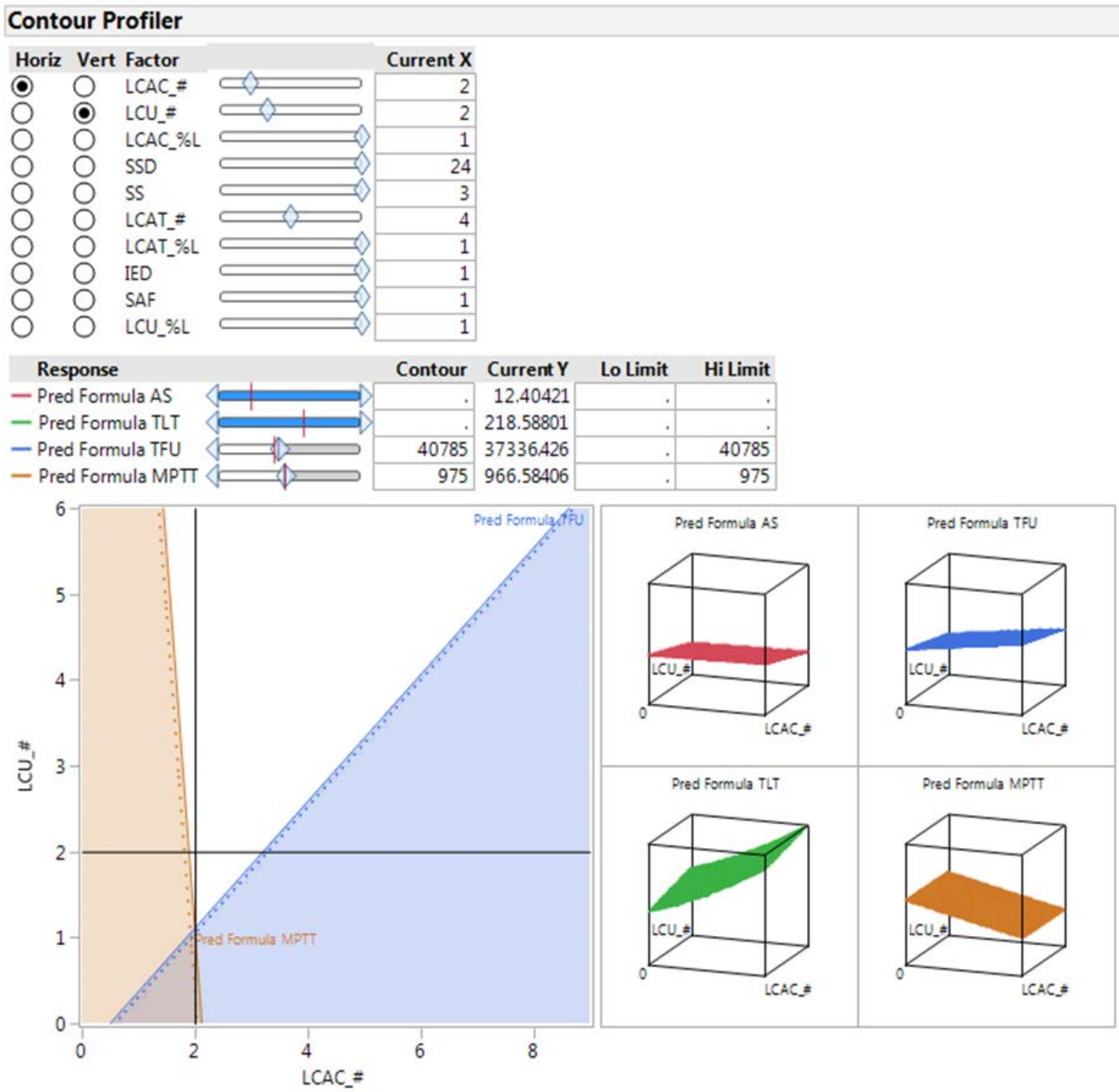

Figure 100. Scenario 6 Solution Space Contour Plot

Scenario #6		
LCU	LCAC	LCAT
2	2	4

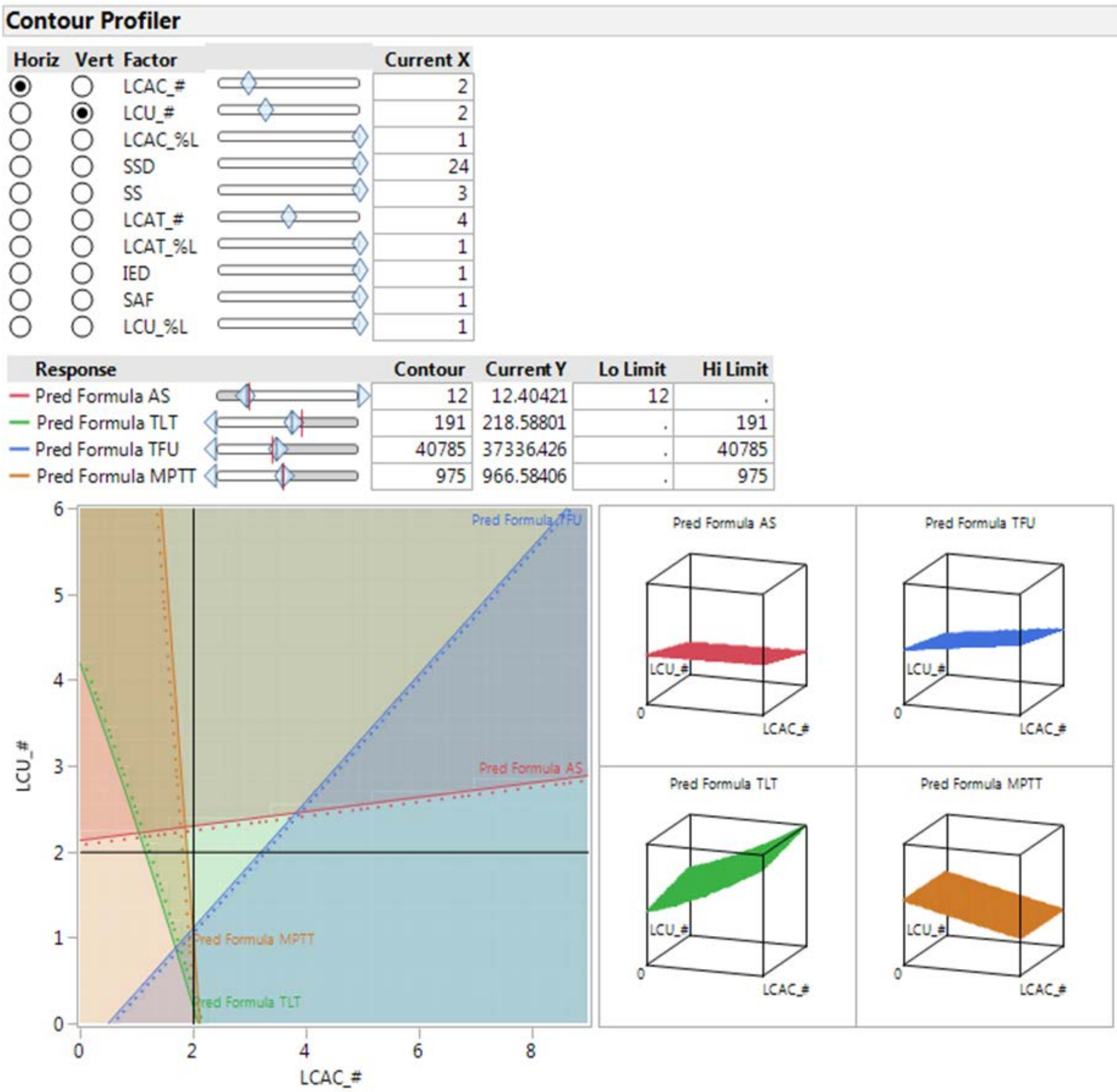

Figure 101. Scenario 6 Solution Space with TLT and AS Contour Plot

Scenario #7		
LCU	LCAC	LCAT
5	0	1

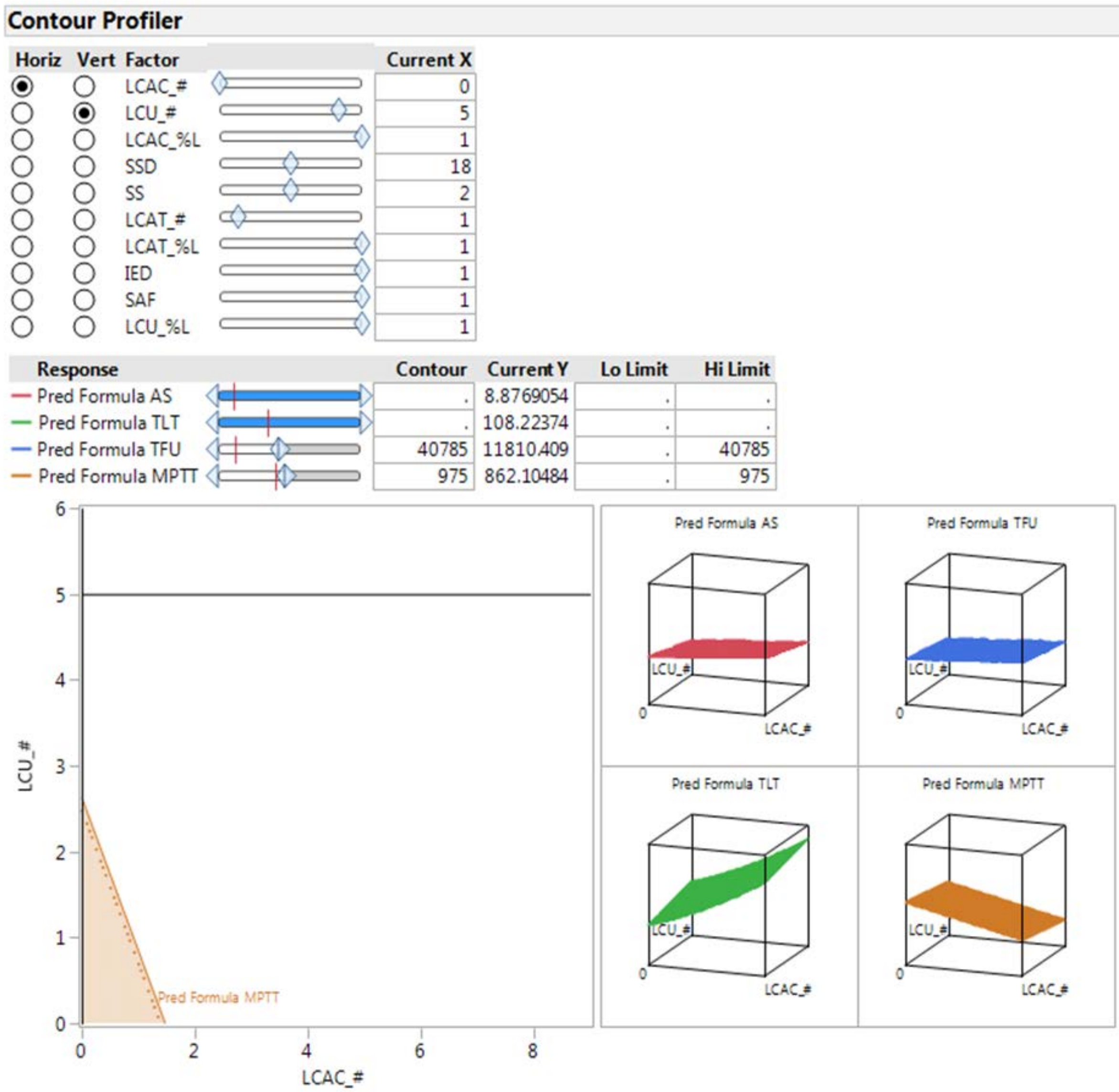

Figure 102. Scenario 7 Solution Space Contour Plot

Scenario #7		
LCU	LCAC	LCAT
5	0	1

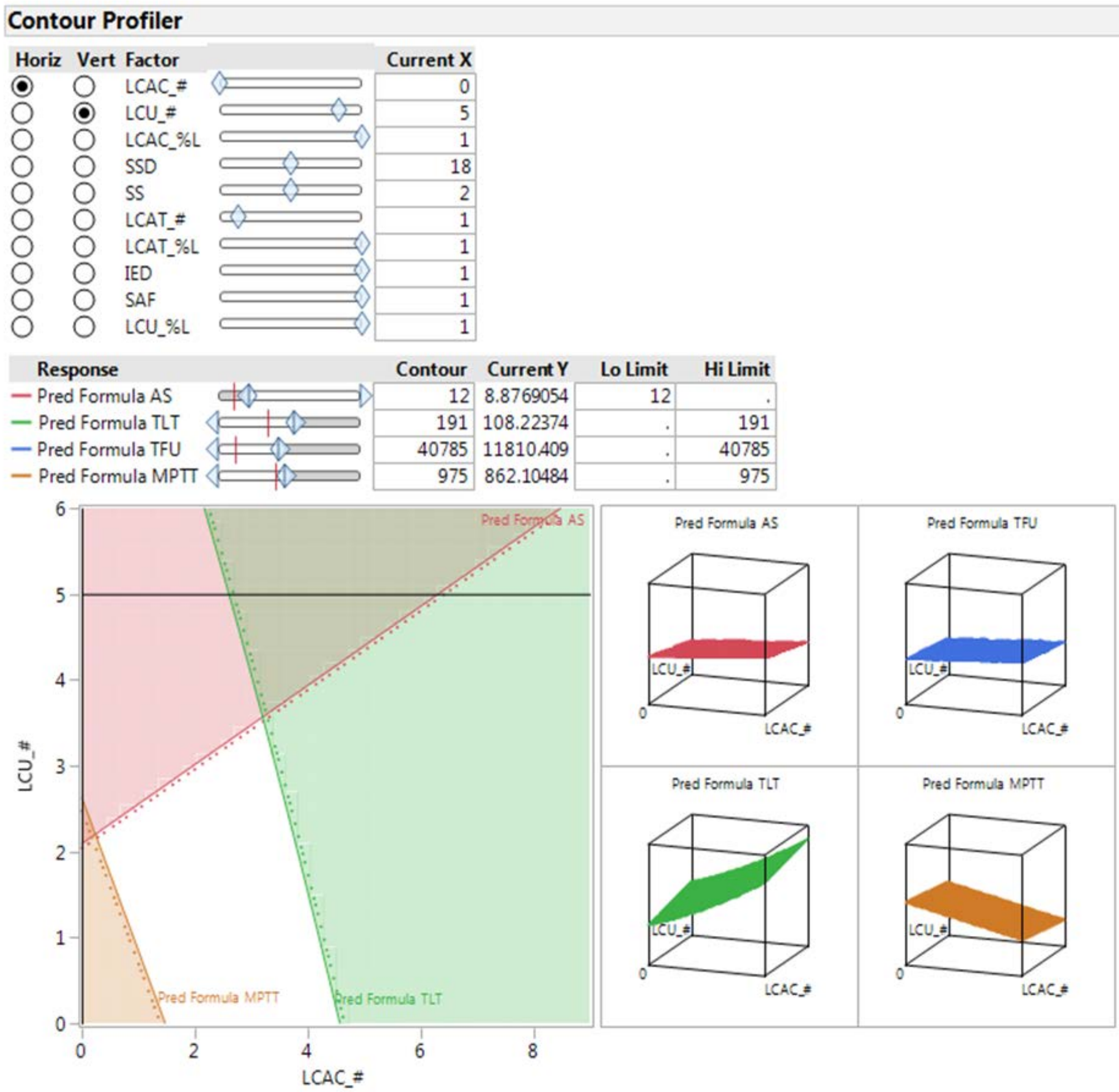

Figure 103. Scenario 7 Solution Space with TLT and AS Contour Plot

Scenario #7		
LCU	LCAC	LCAT
5	0	1

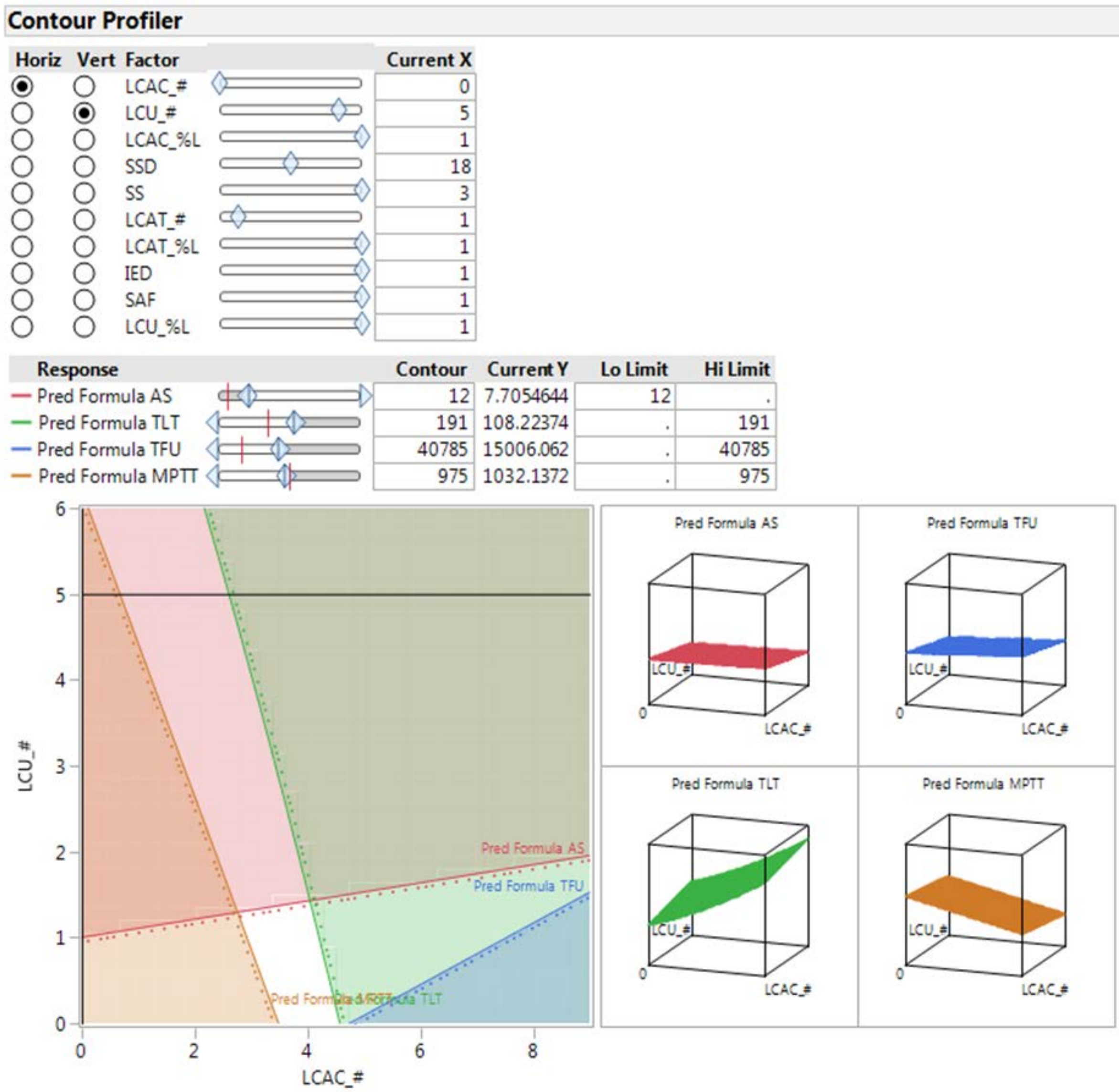

Figure 104. Scenario 7 Limiting Response Contour Plot

Scenario #8		
LCU	LCAC	LCAT
2	4	1

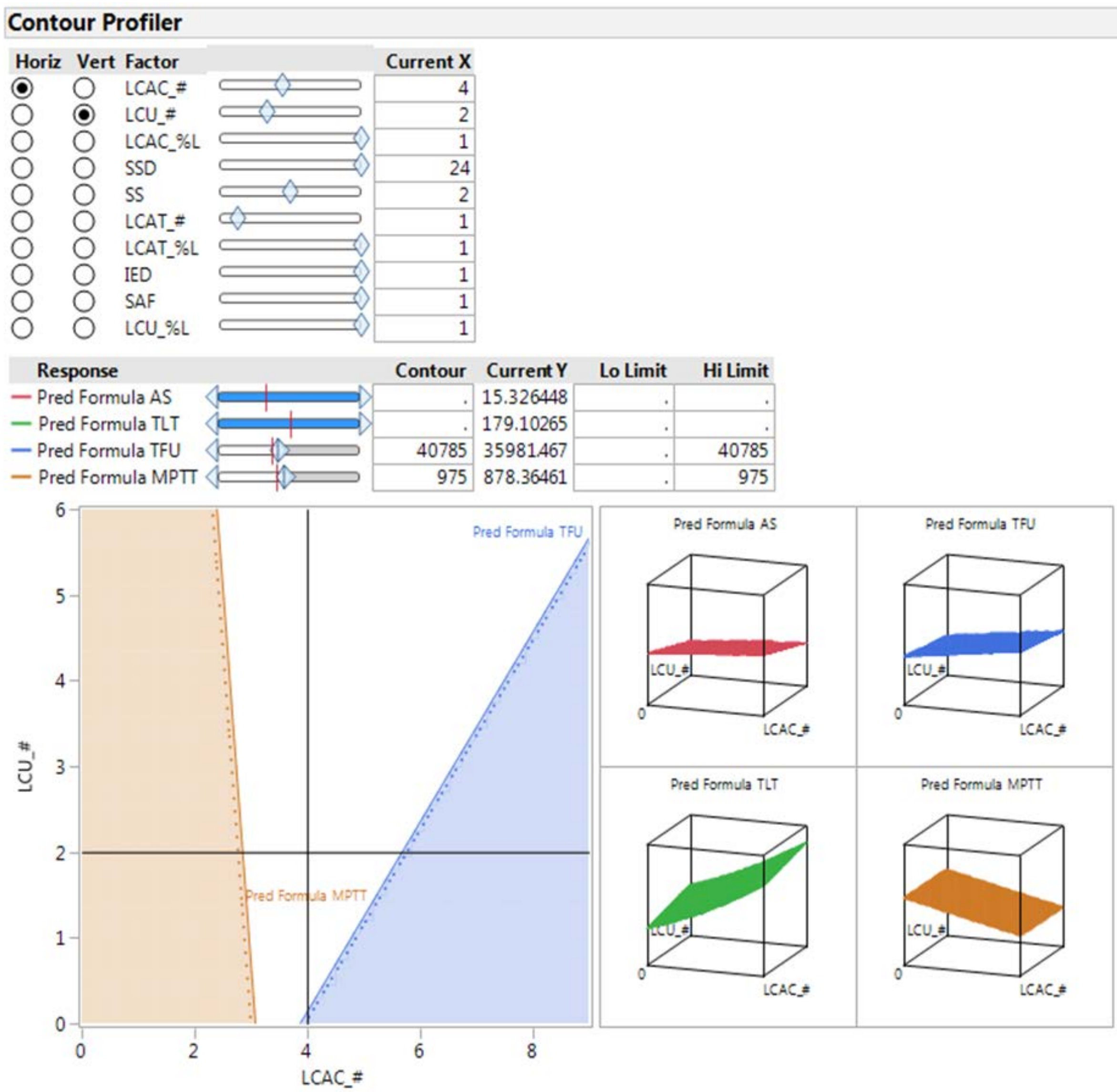

Figure 105. Scenario 8 Solution Space Contour Plot

Scenario #8		
LCU	LCAC	LCAT
2	4	1

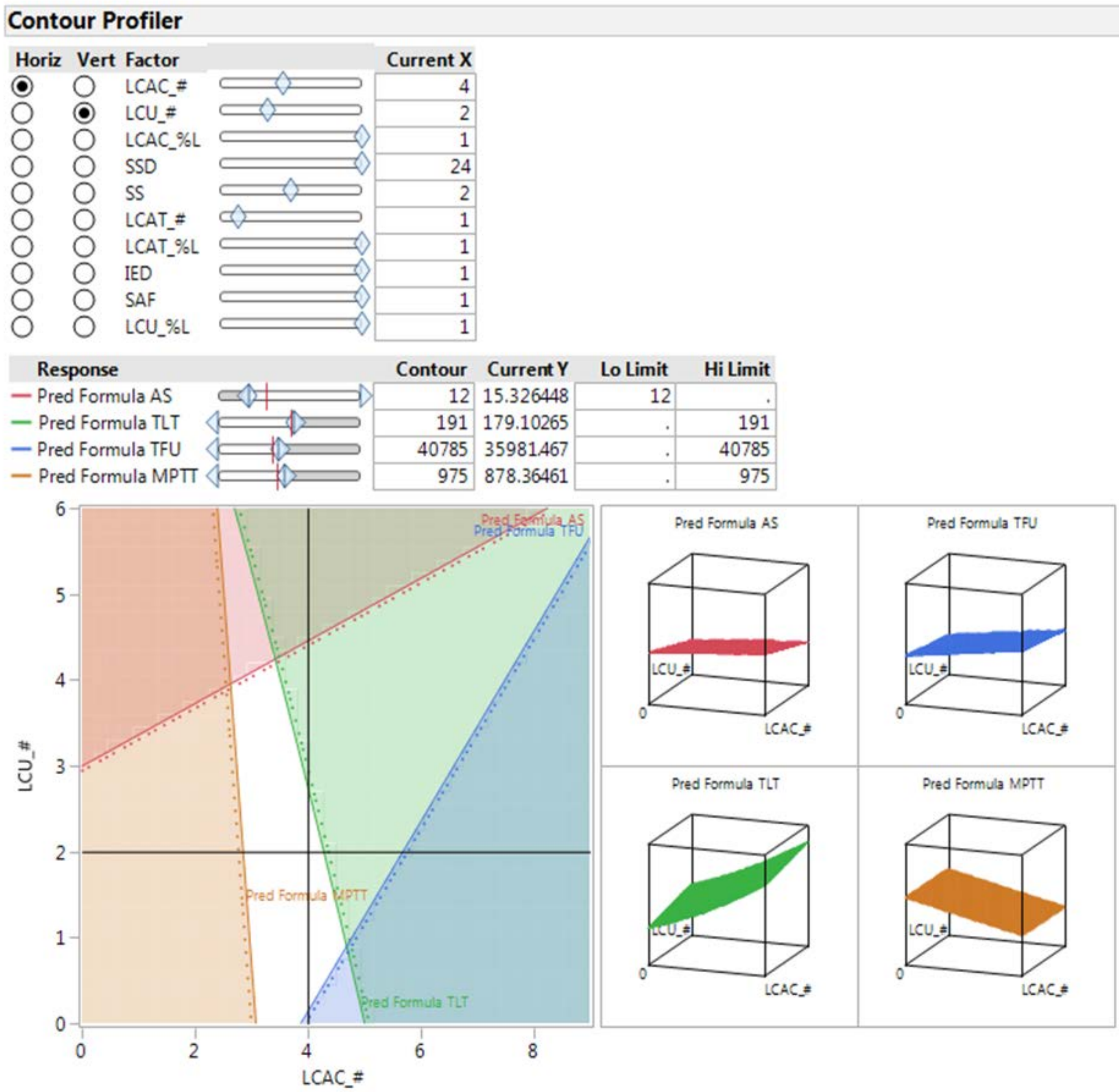

Figure 106. Scenario 8 Solution Space with TLT and AS Contour Plot

Scenario #8		
LCU	LCAC	LCAT
2	4	1

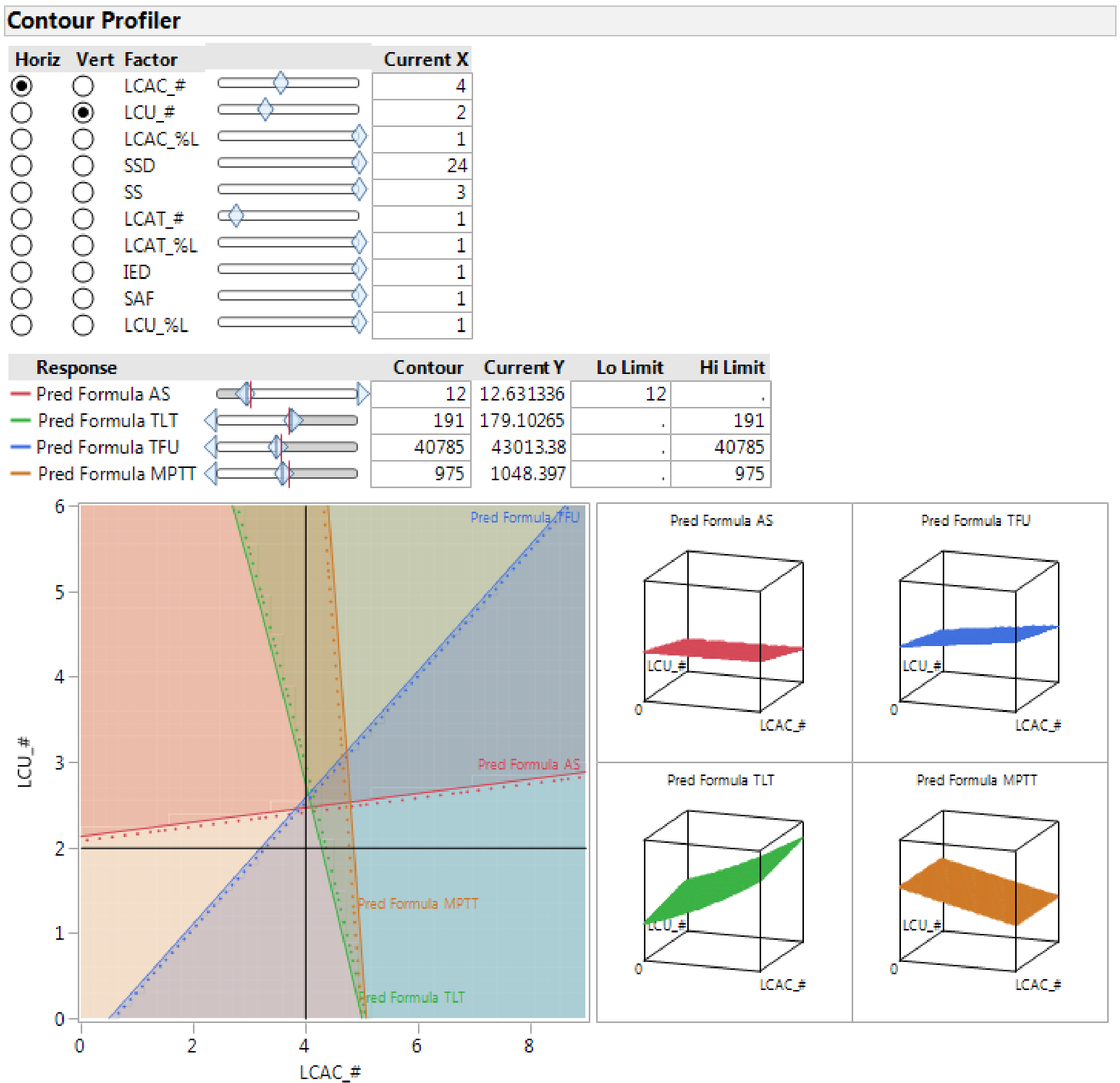

Figure 107. Scenario 8 Limiting Response Contour Plot

Scenario #9		
LCU	LCAC	LCAT
0	3	5

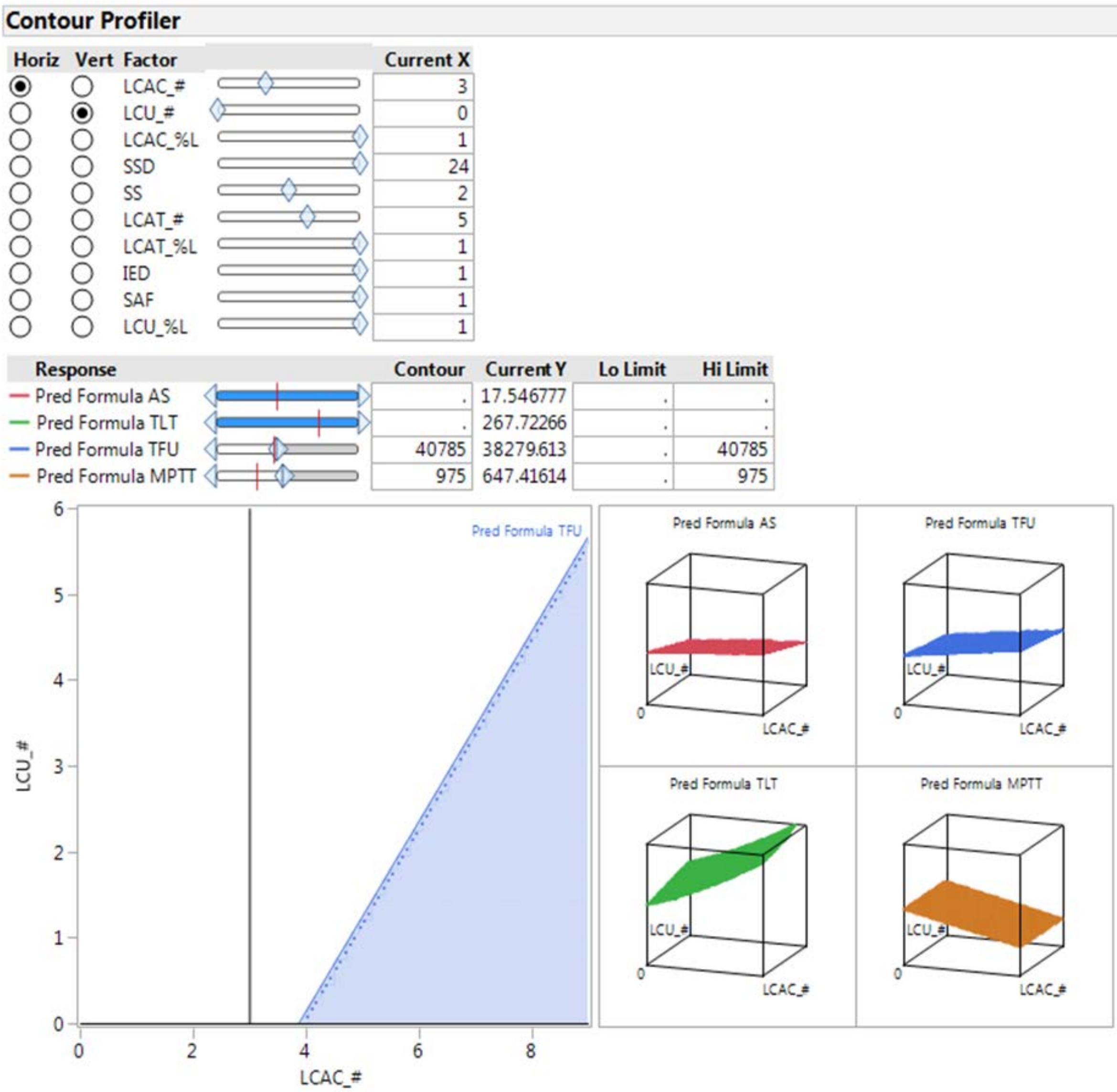

Figure 108. Scenario 9 Solution Space Contour Plot

Scenario #9		
LCU	LCAC	LCAT
0	3	5

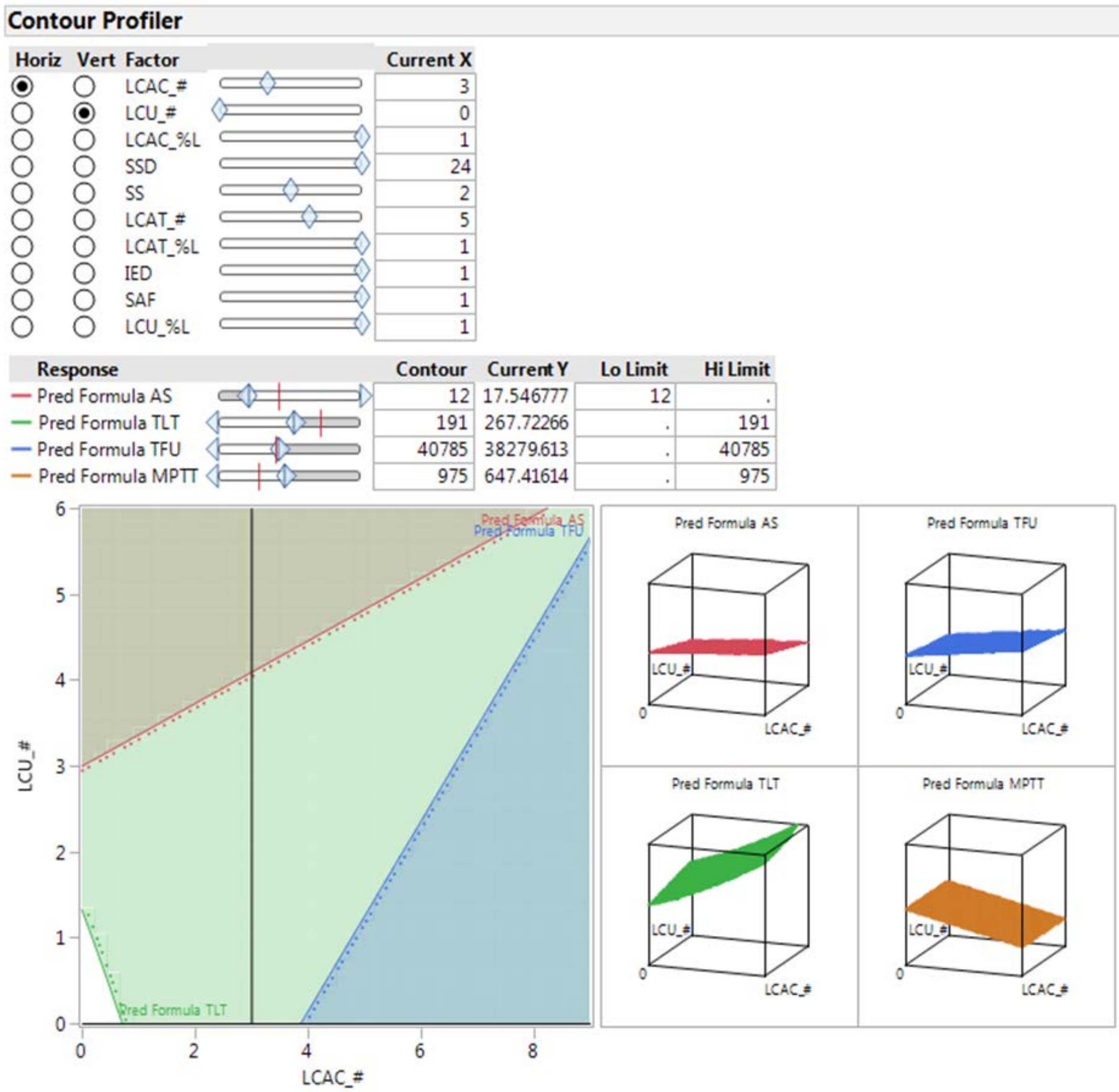

Figure 109. Scenario 9 Solution Space with TLT and AS Contour Plot

Scenario #9		
LCU	LCAC	LCAT
0	3	5

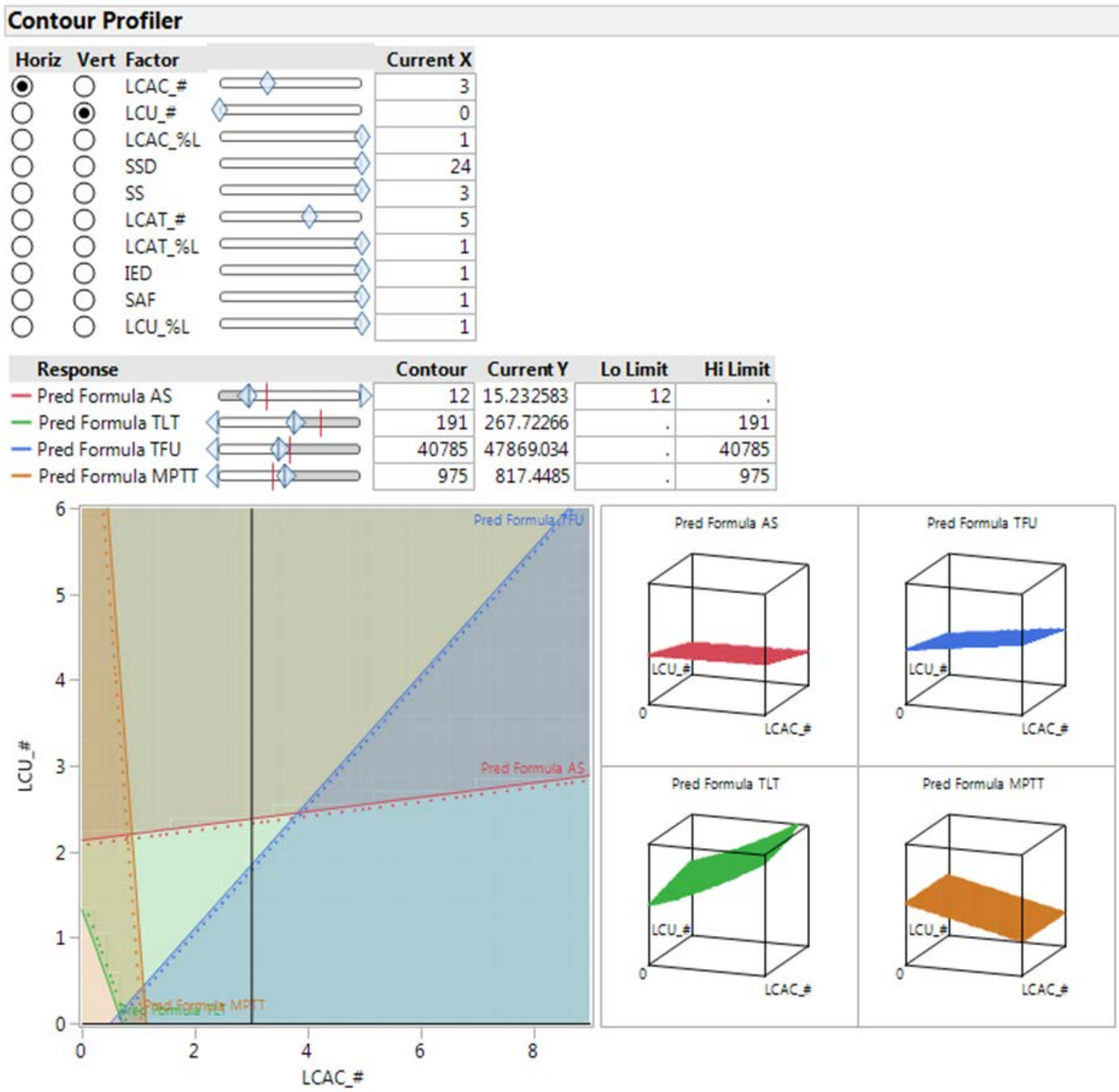

Figure 110. Scenario 9 Limiting Response Contour Plot

Scenario #10		
LCU	LCAC	LCAT
4	3	0

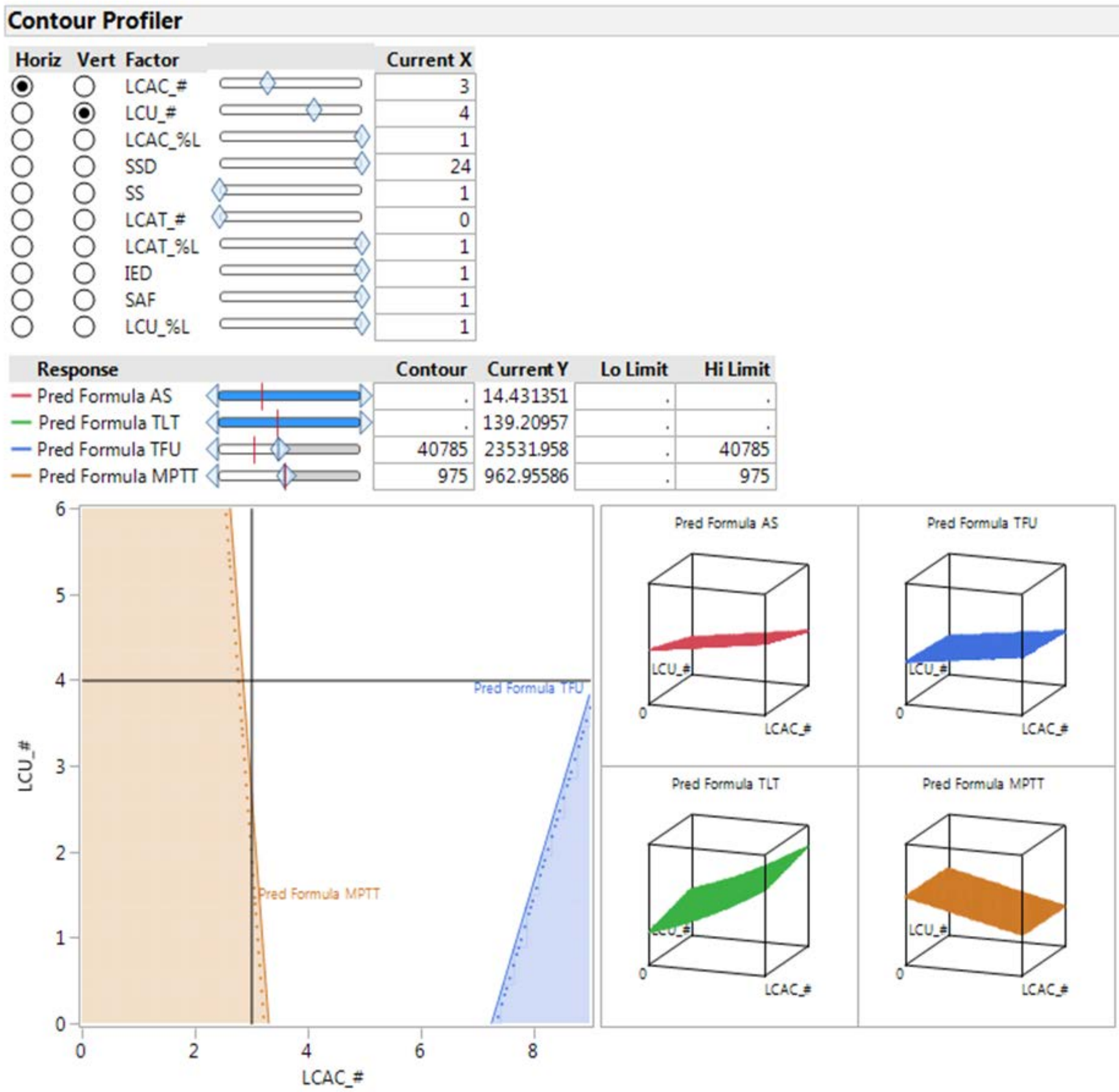

Figure 111. Scenario 10 Solution Space Contour Plot

Scenario #10		
LCU	**LCAC**	**LCAT**
4	3	0

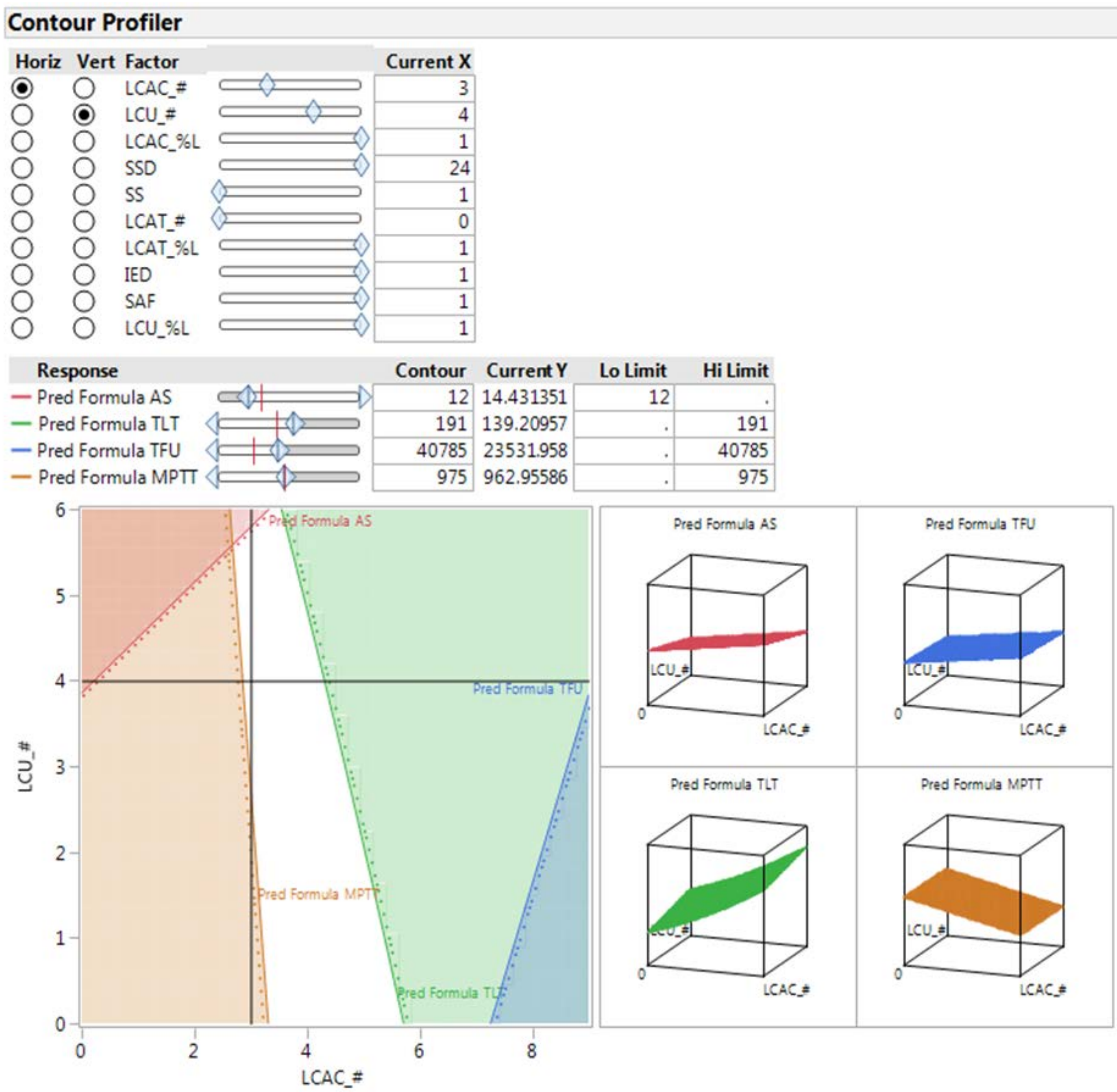

Figure 112. Scenario 10 Solution Space with TLT and AS Contour Plot

Scenario #10		
LCU	**LCAC**	**LCAT**
4	3	0

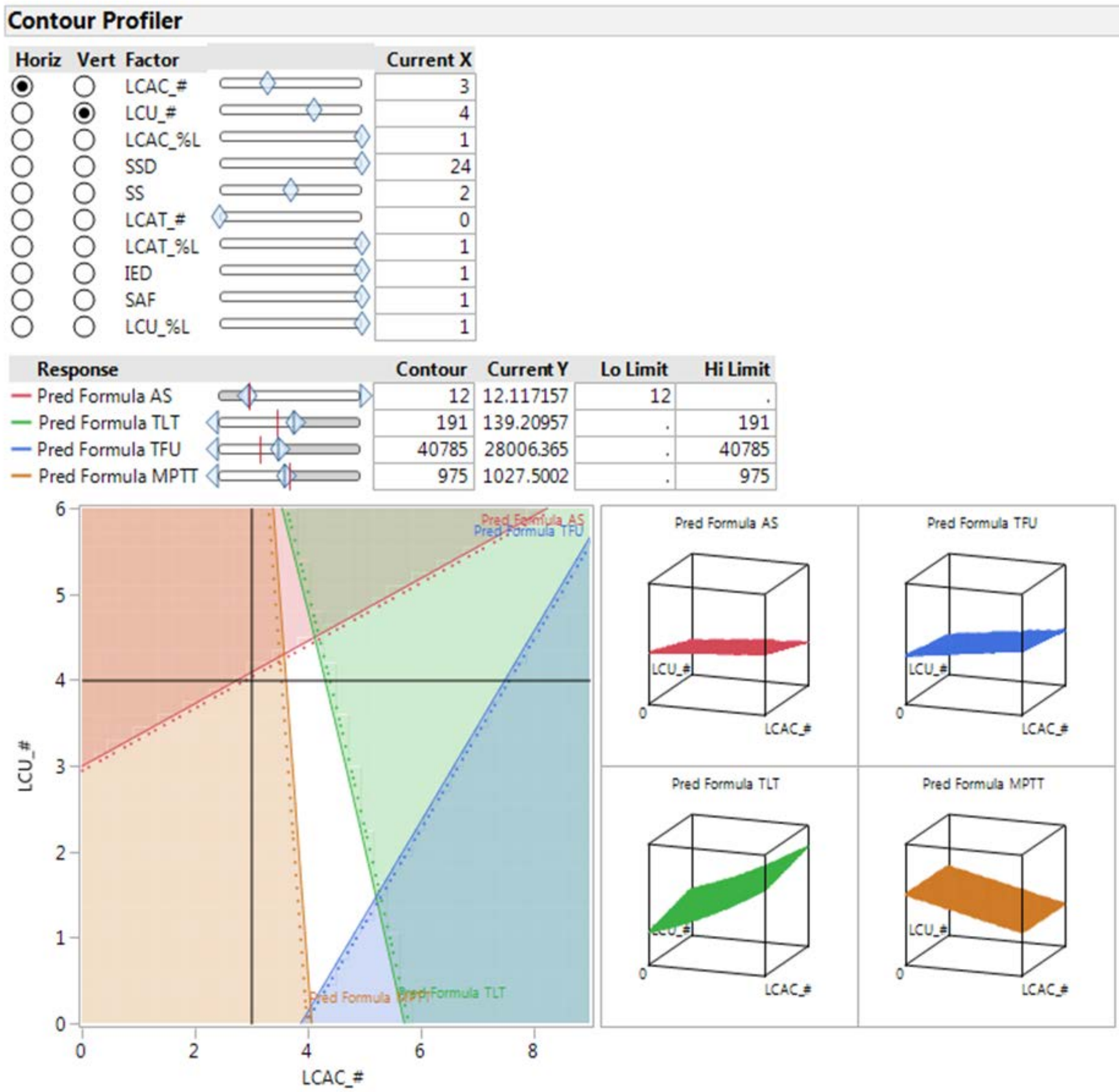

Figure 113. Scenario 10 Limiting Response Contour Plot

Scenario #11		
LCU	LCAC	LCAT
1	7	0

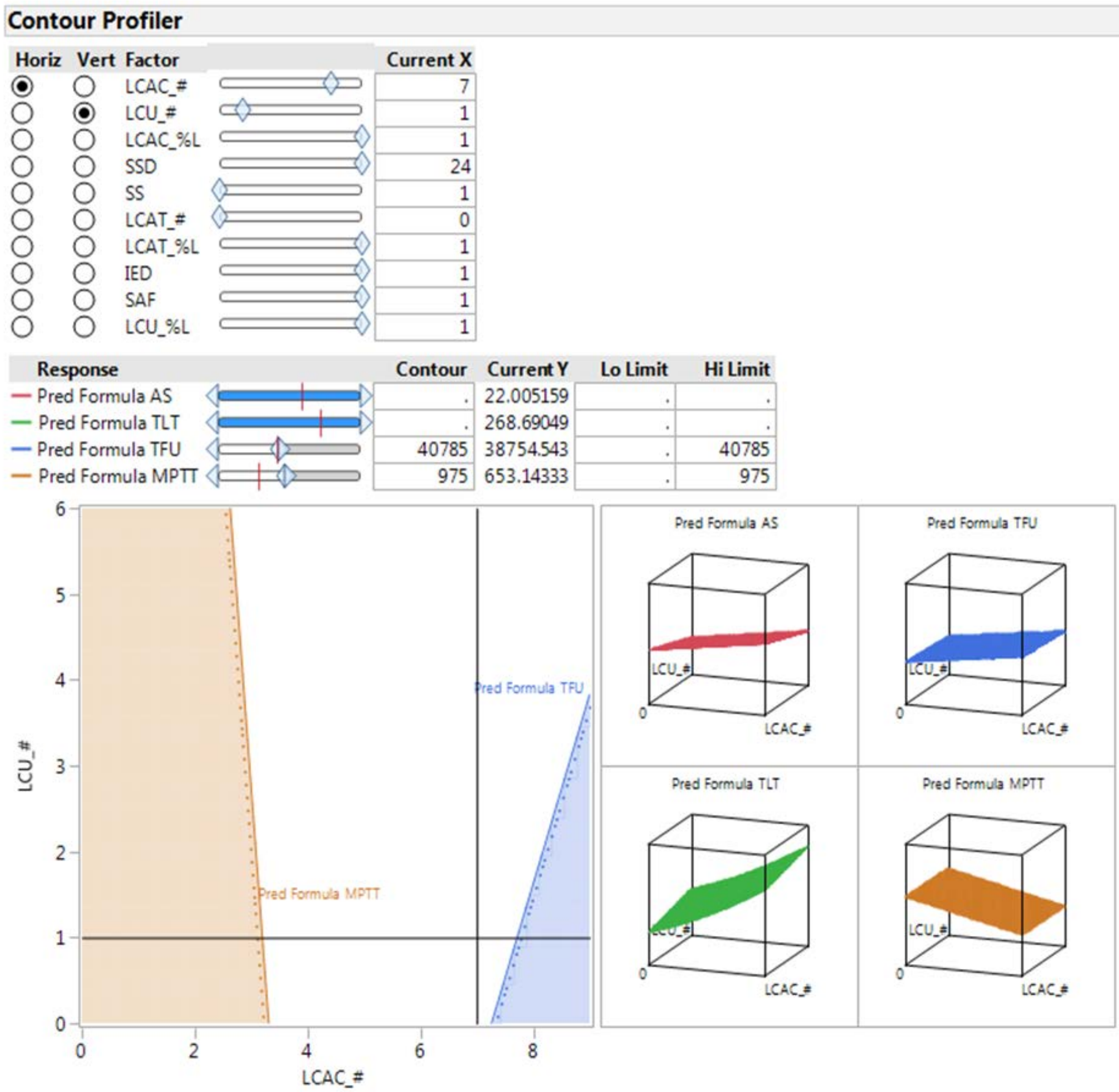

Figure 114. Scenario 11 Solution Space Contour Plot

Scenario #11		
LCU	LCAC	LCAT
1	7	0

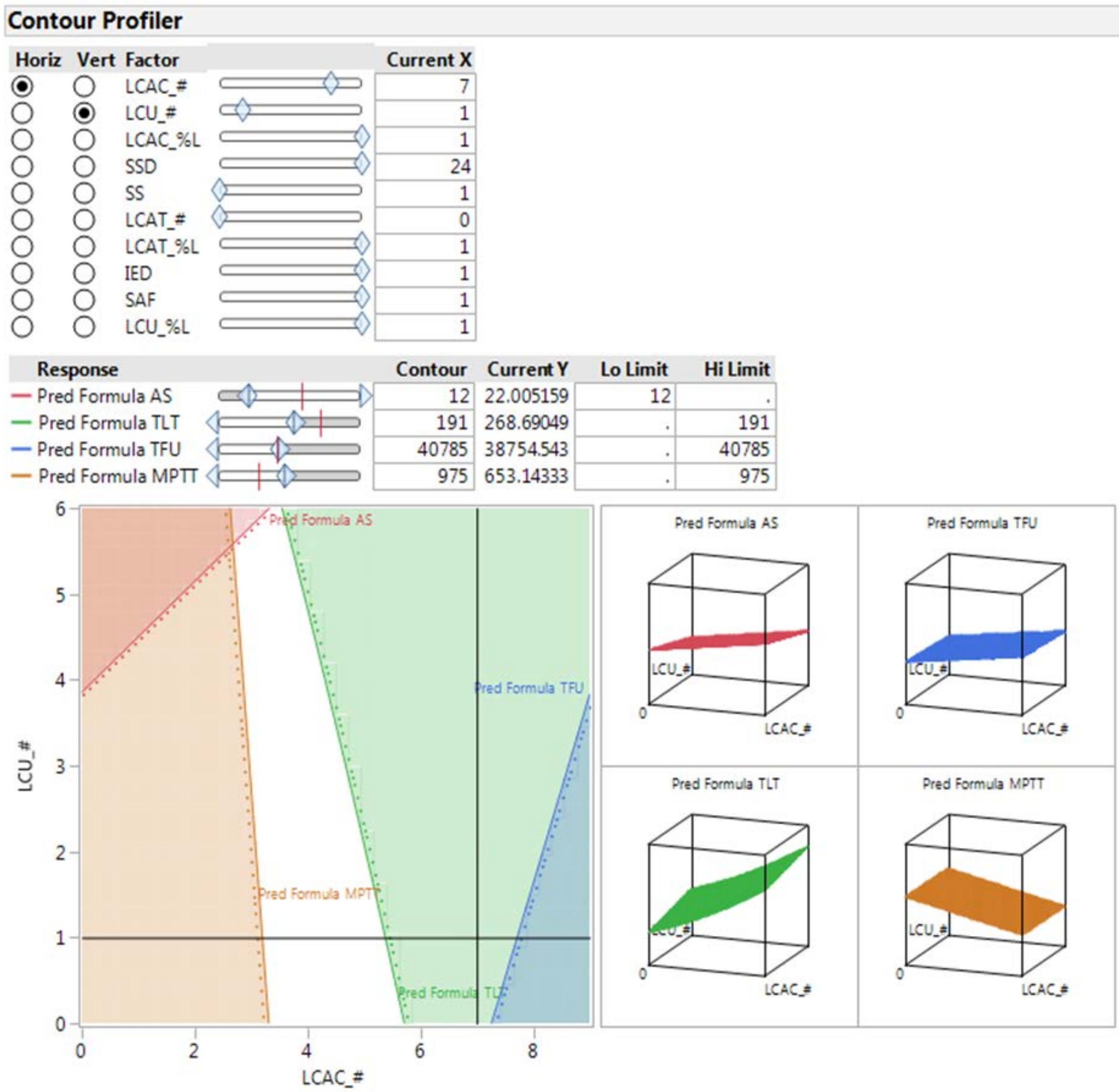

Figure 115. Scenario 11 Solution Space with TLT and AS Contour Plot

Scenario #11		
LCU	LCAC	LCAT
1	7	0

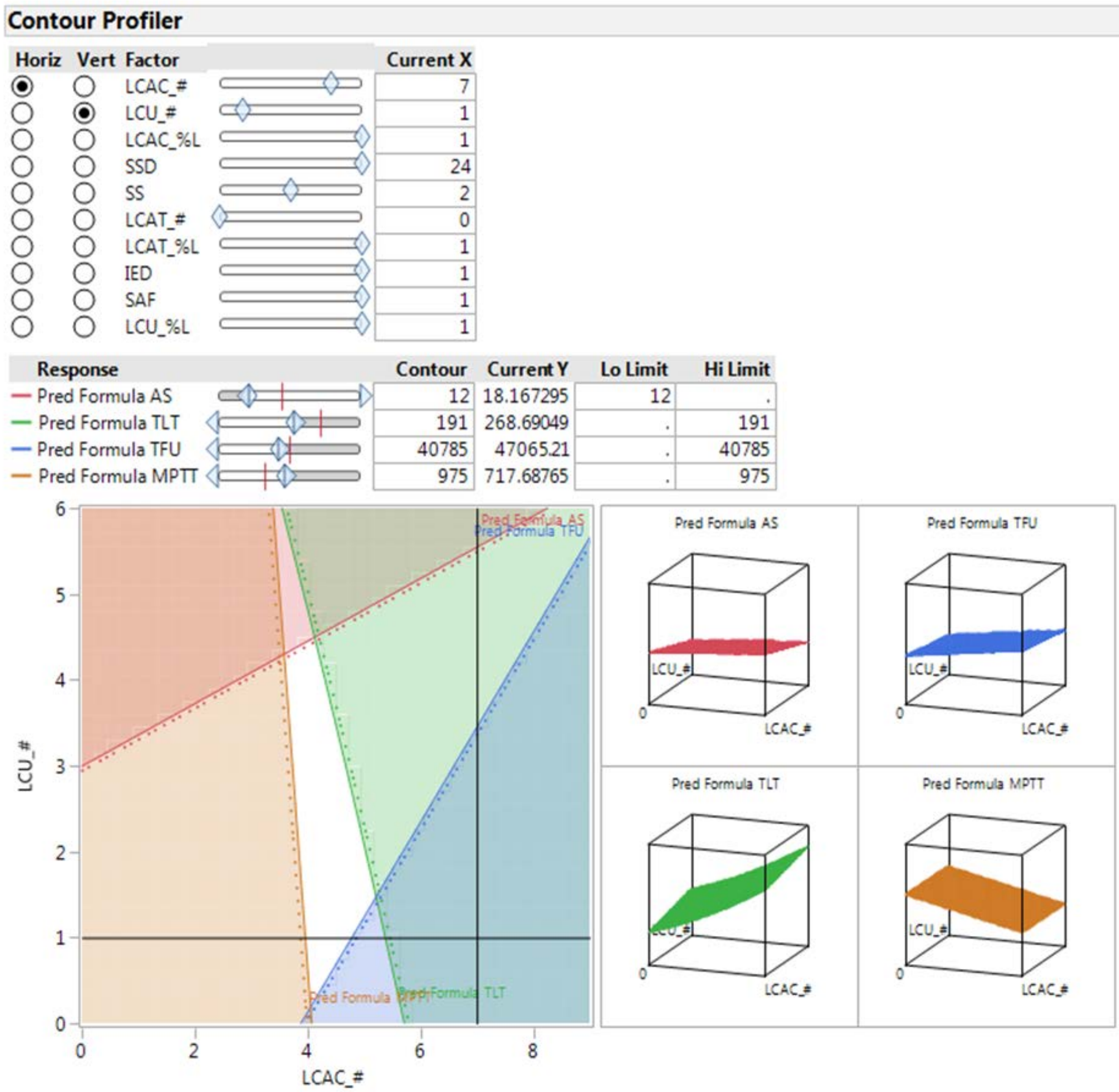

Figure 116. Scenario 11 Limiting Response Contour Plot

Scenario #12		
LCU	LCAC	LCAT
1	3	4

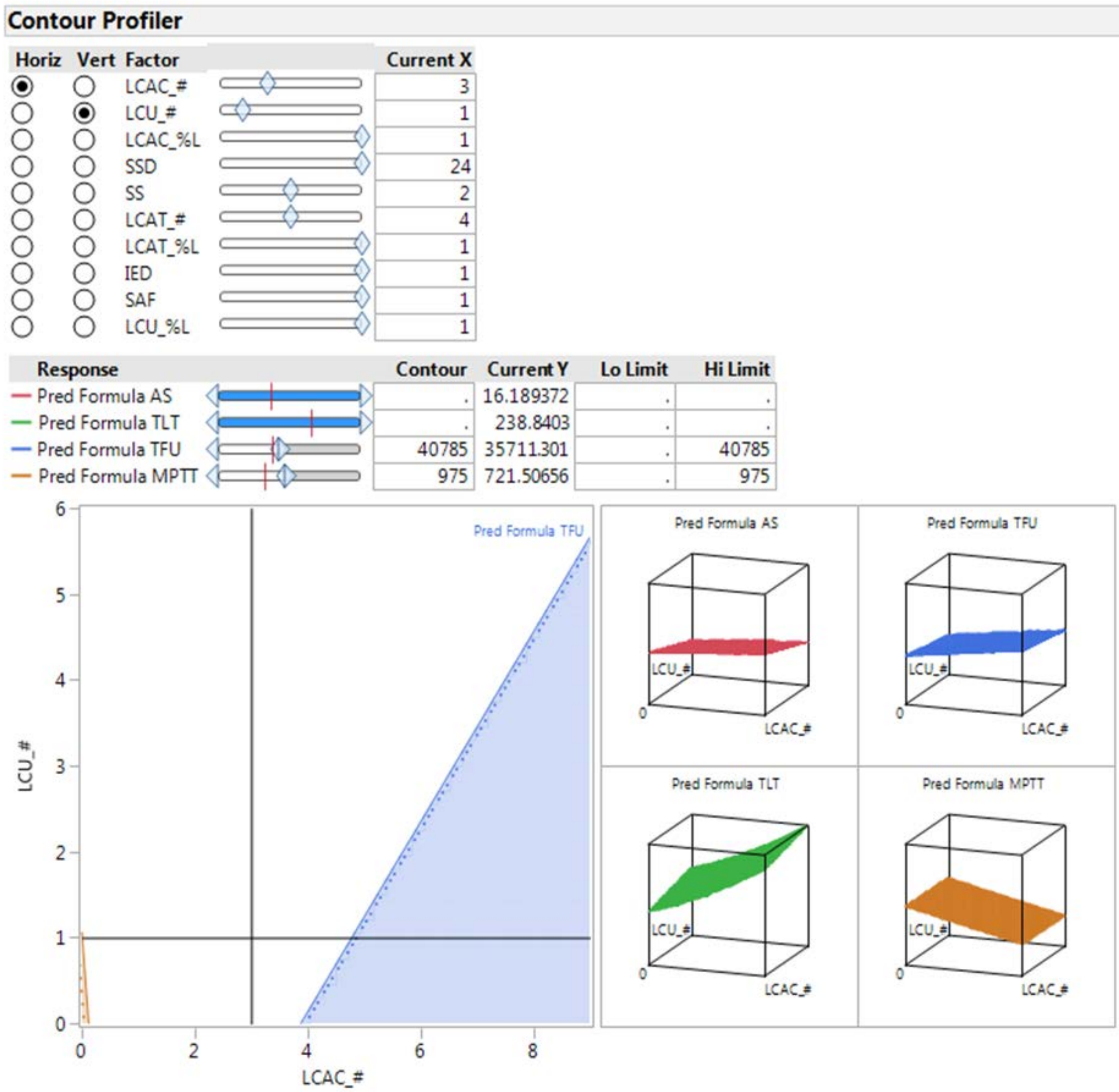

Figure 117. Scenario 12 Solution Space Contour Plot

Scenario #12		
LCU	**LCAC**	**LCAT**
1	3	4

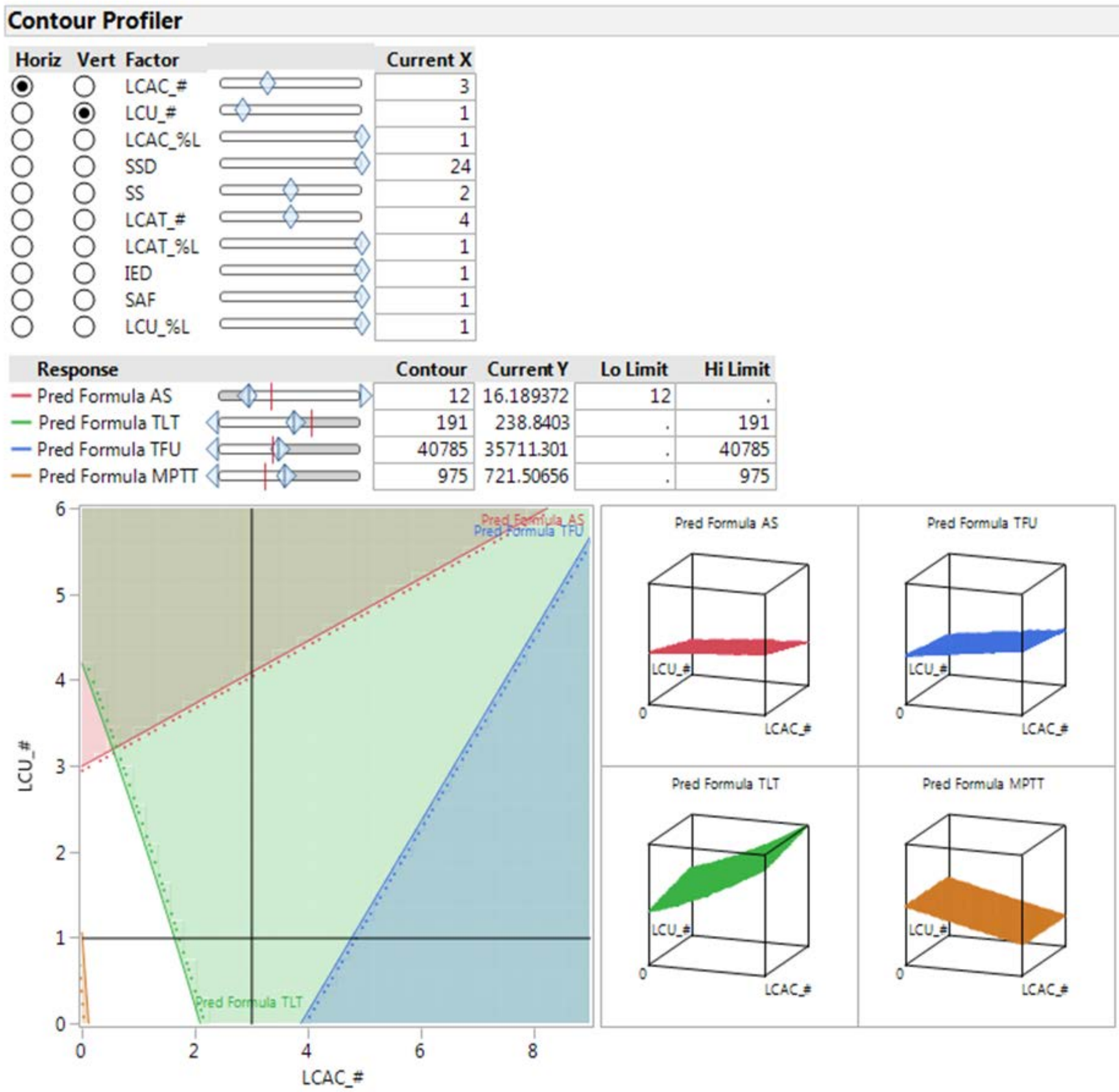

Figure 118. Scenario 12 Solution Space with TLT and AS Contour Plot

Scenario #12		
LCU	**LCAC**	**LCAT**
1	3	4

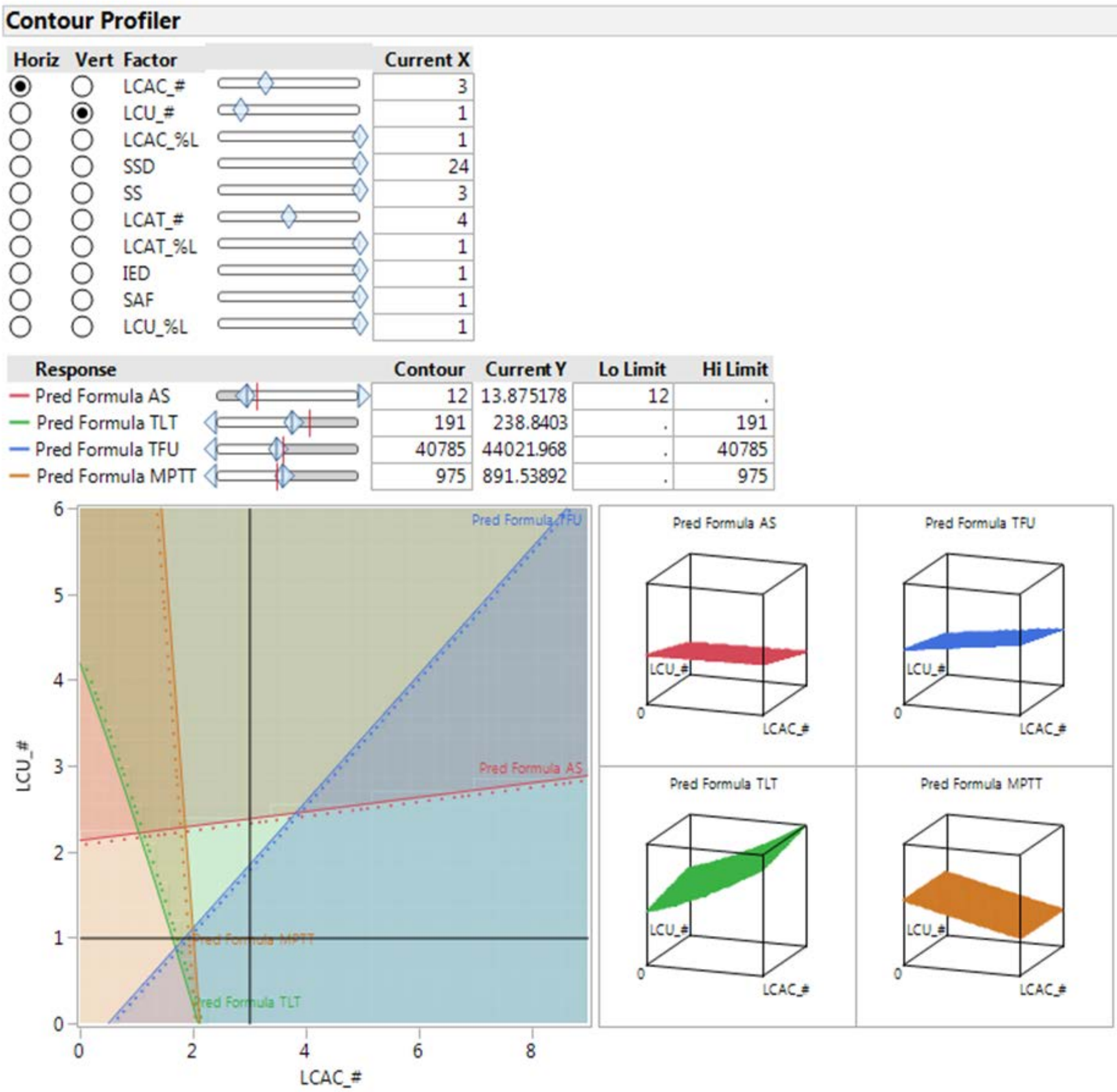

Figure 119. Scenario 12 Limiting Response Contour Plot

Scenario #13		
LCU	LCAC	LCAT
3	5	0

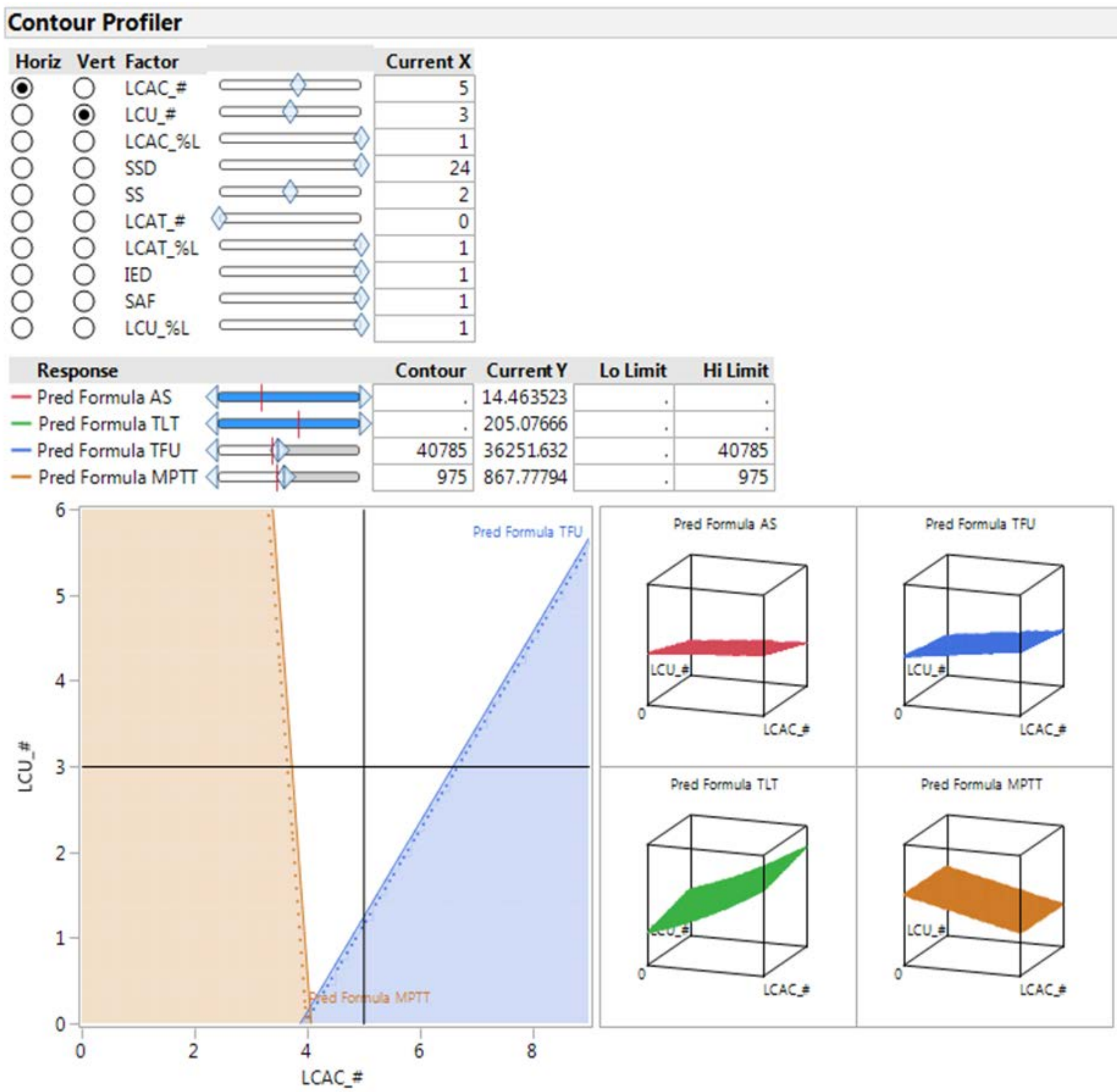

Figure 120. Scenario 13 Solution Space Contour Plot

Scenario #13		
LCU	LCAC	LCAT
3	5	0

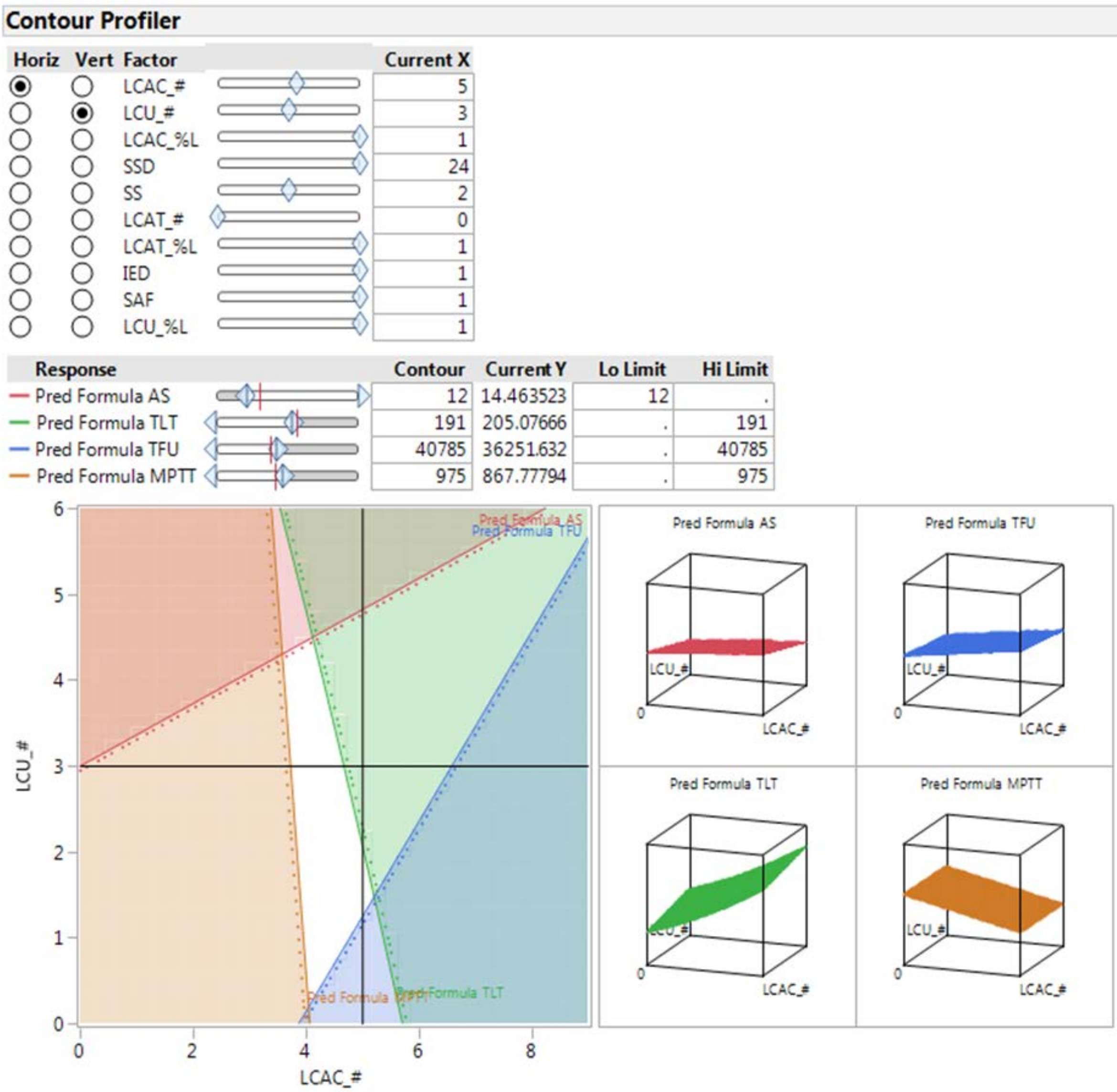

Figure 121. Scenario 13 Solution Space with TLT and AS Contour Plot

Scenario #13		
LCU	**LCAC**	**LCAT**
3	5	0

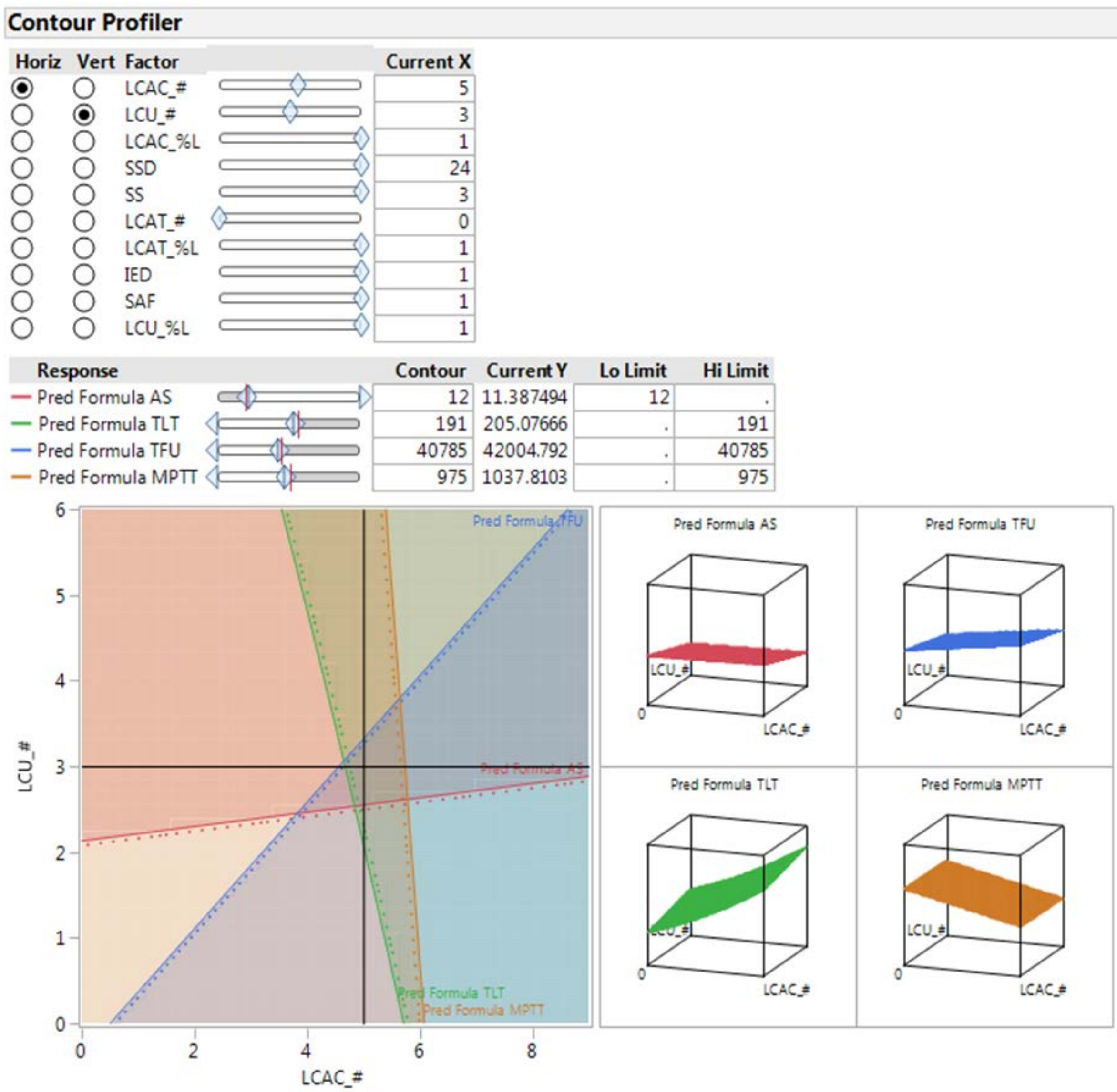

Figure 122. Scenario 13 Limiting Response Contour Plot

Scenario #14		
LCU	LCAC	LCAT
0	9	0

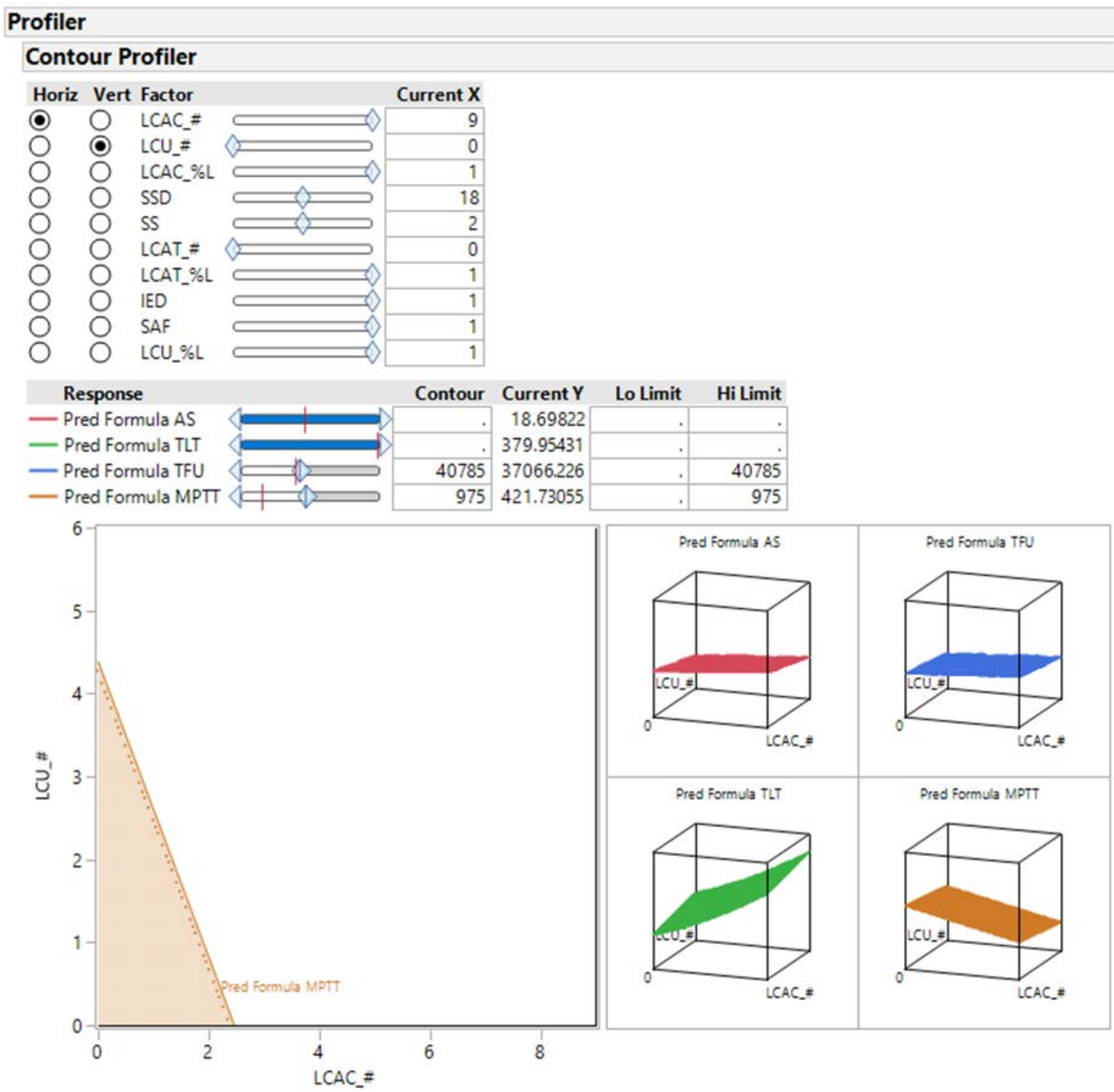

Figure 123. Scenario 14 Solution Space Contour Plot

Scenario #14		
LCU	LCAC	LCAT
0	9	0

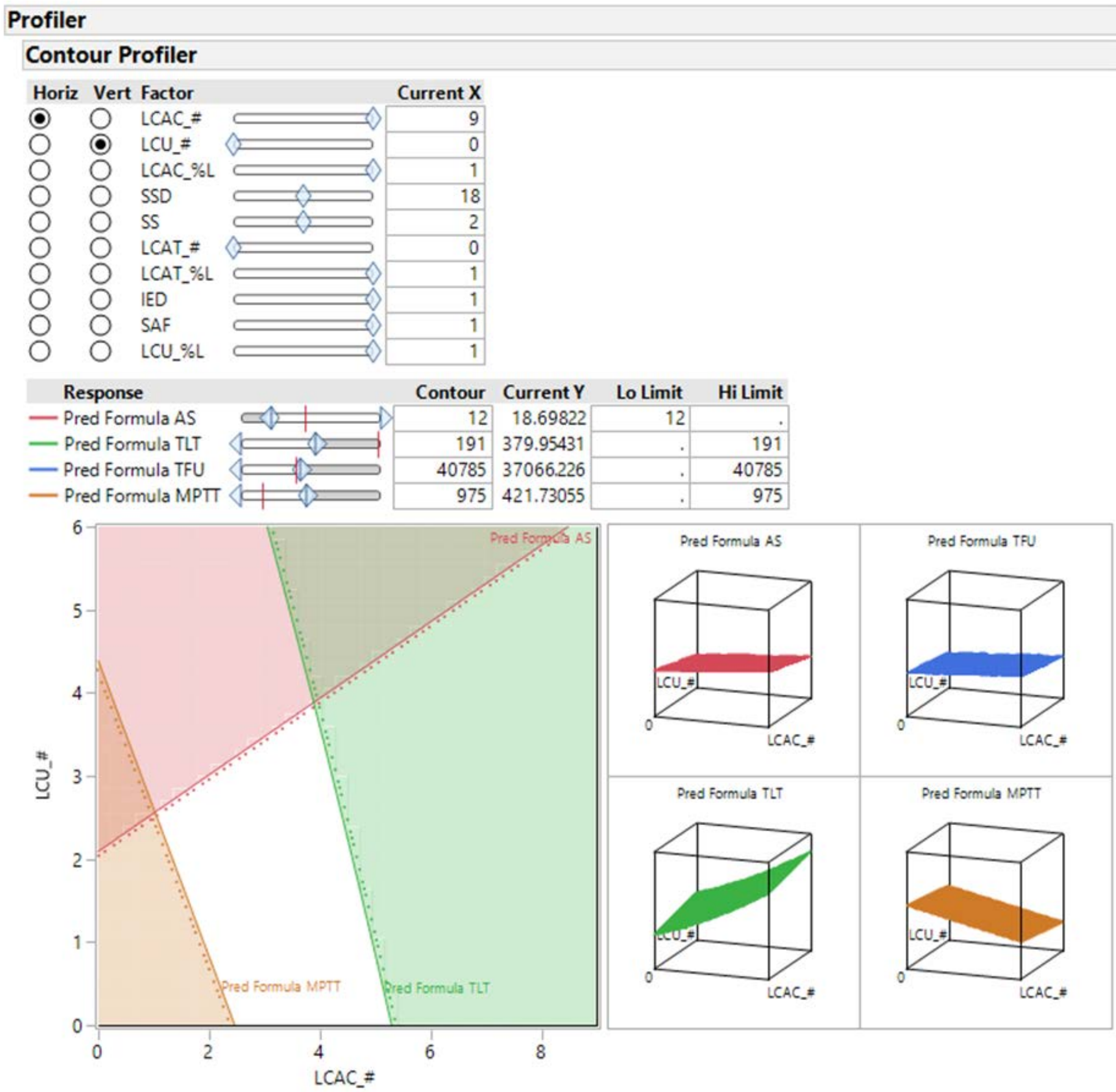

Figure 124. Scenario 14 Solution Space with TLT and AS Contour Plot

Scenario #14		
LCU	LCAC	LCAT
0	9	0

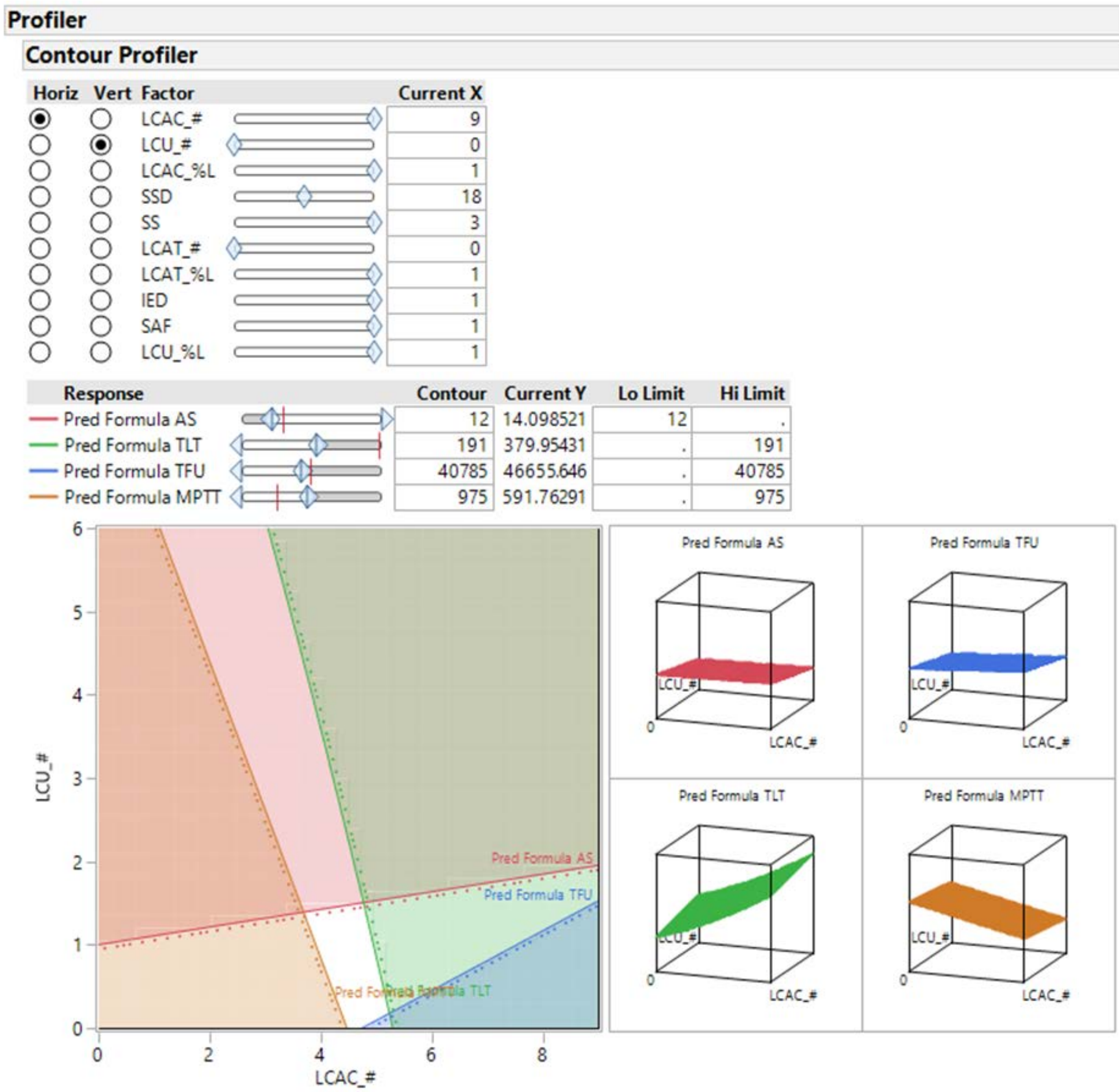

Figure 125. Scenario 14 Limiting Response Contour Plot

Scenario #15		
LCU	LCAC	LCAT
0	5	4

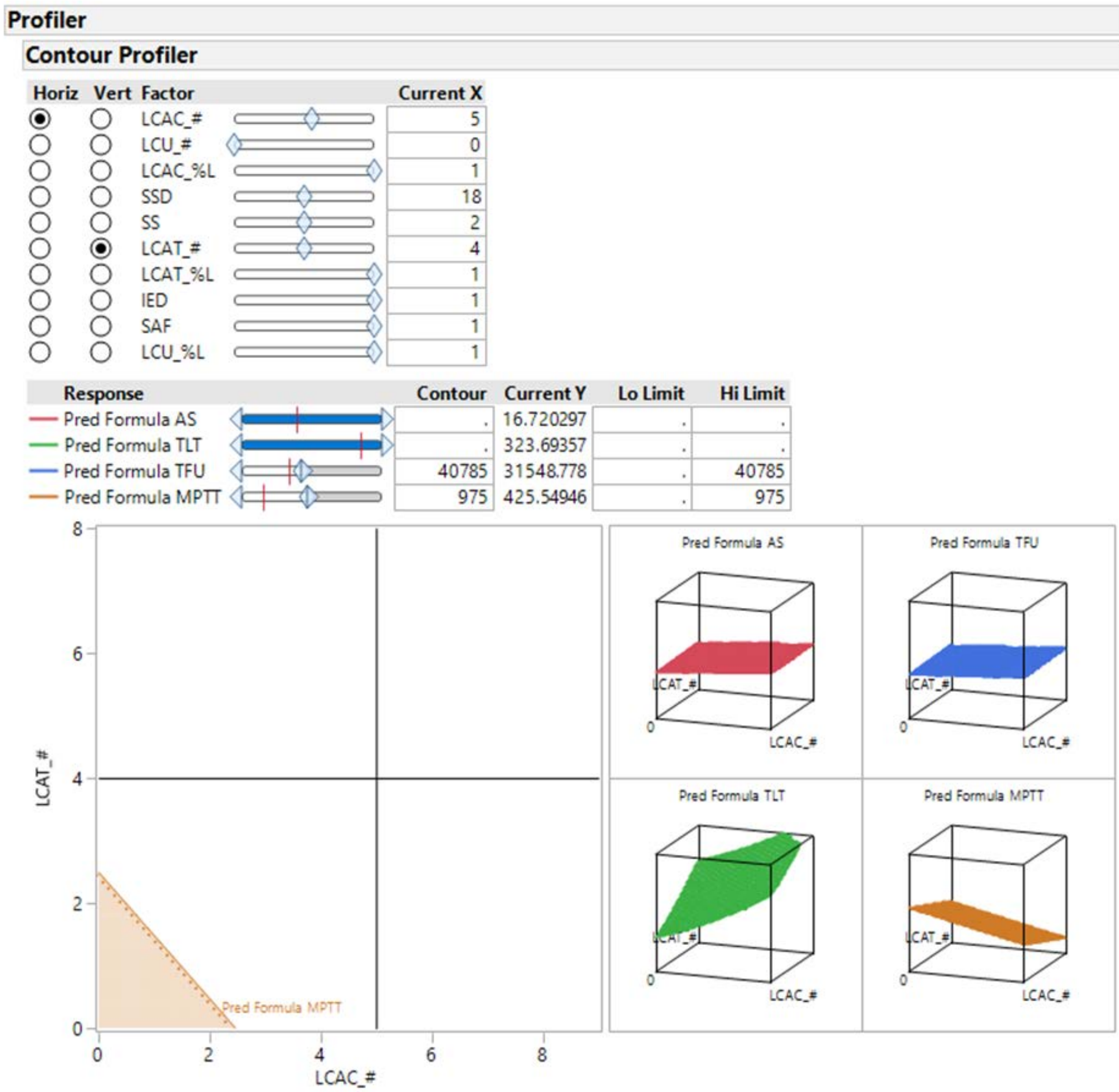

Figure 126. Scenario 15 Solution Space Contour Plot

Scenario #15		
LCU	LCAC	LCAT
0	5	4

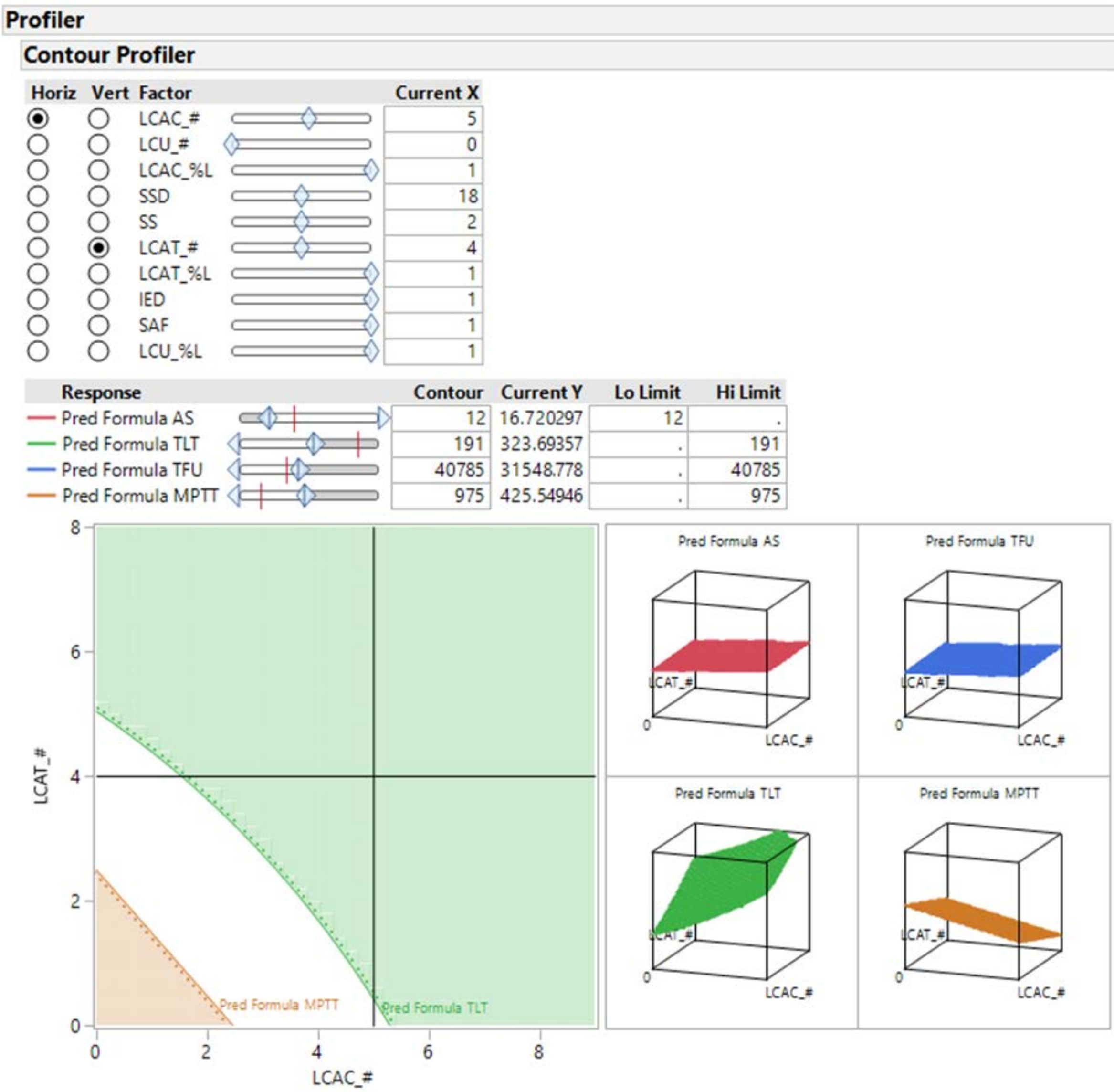

Figure 127. Scenario 15 Solution Space with TLT and AS Contour Plot

Scenario #15		
LCU	**LCAC**	**LCAT**
0	5	4

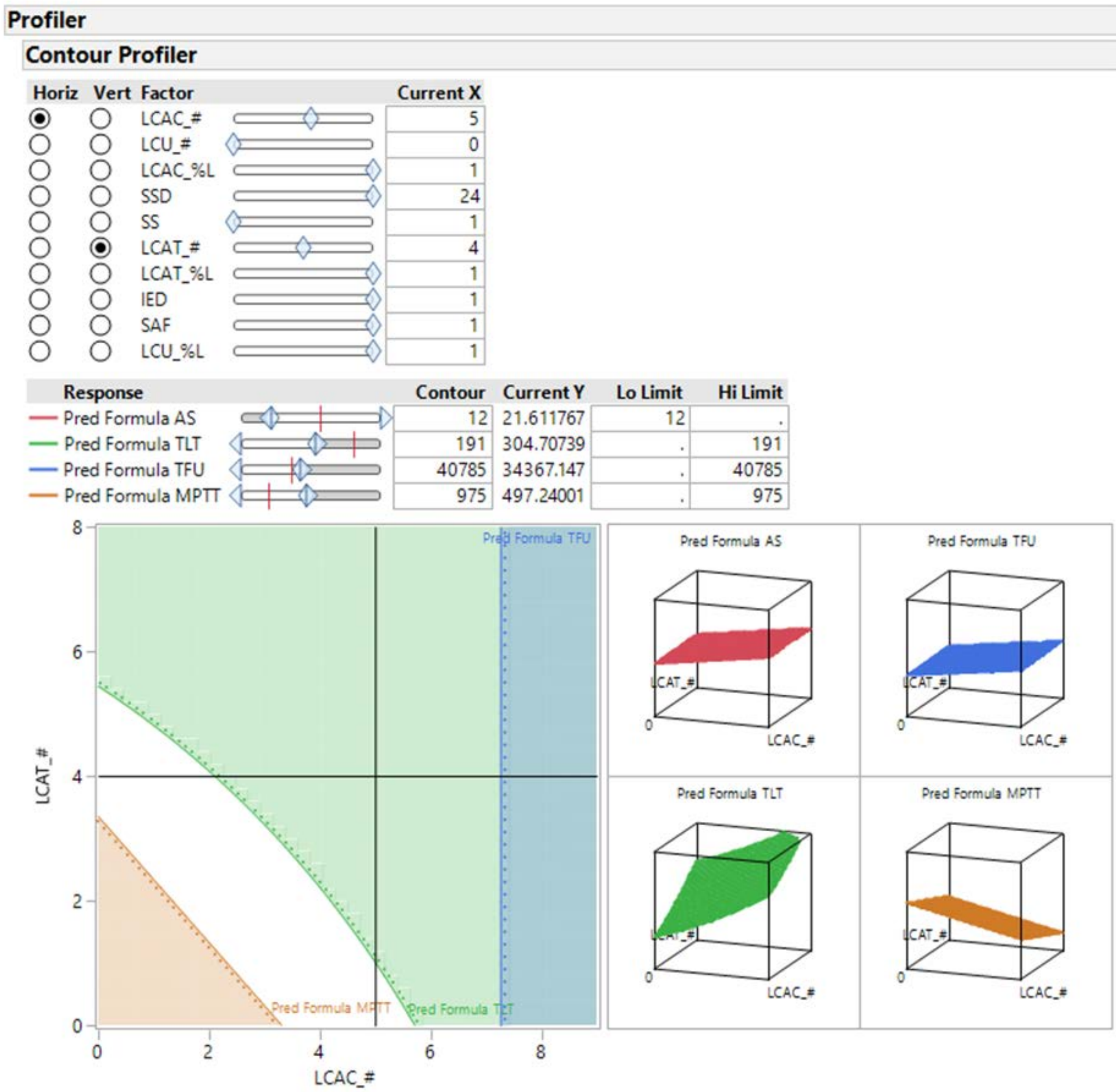

Figure 128. Scenario 15 Solution Space 2 with TLT and AS Contour Plot

Scenario #15		
LCU	LCAC	LCAT
0	5	4

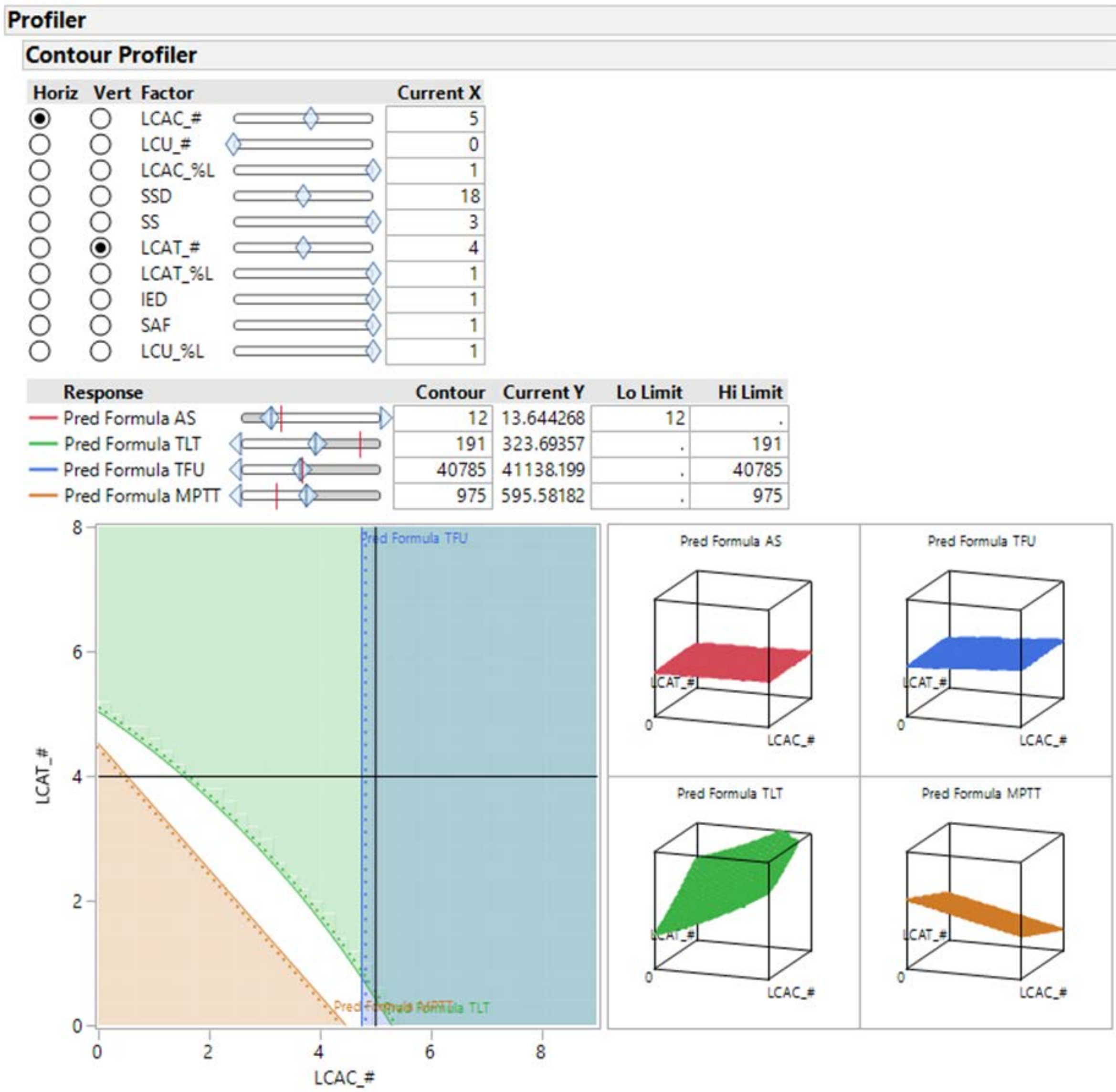

Figure 129. Scenario 15 Limiting Response Contour Plot

Scenario #16		
LCU	LCAC	LCAT
3	3	1

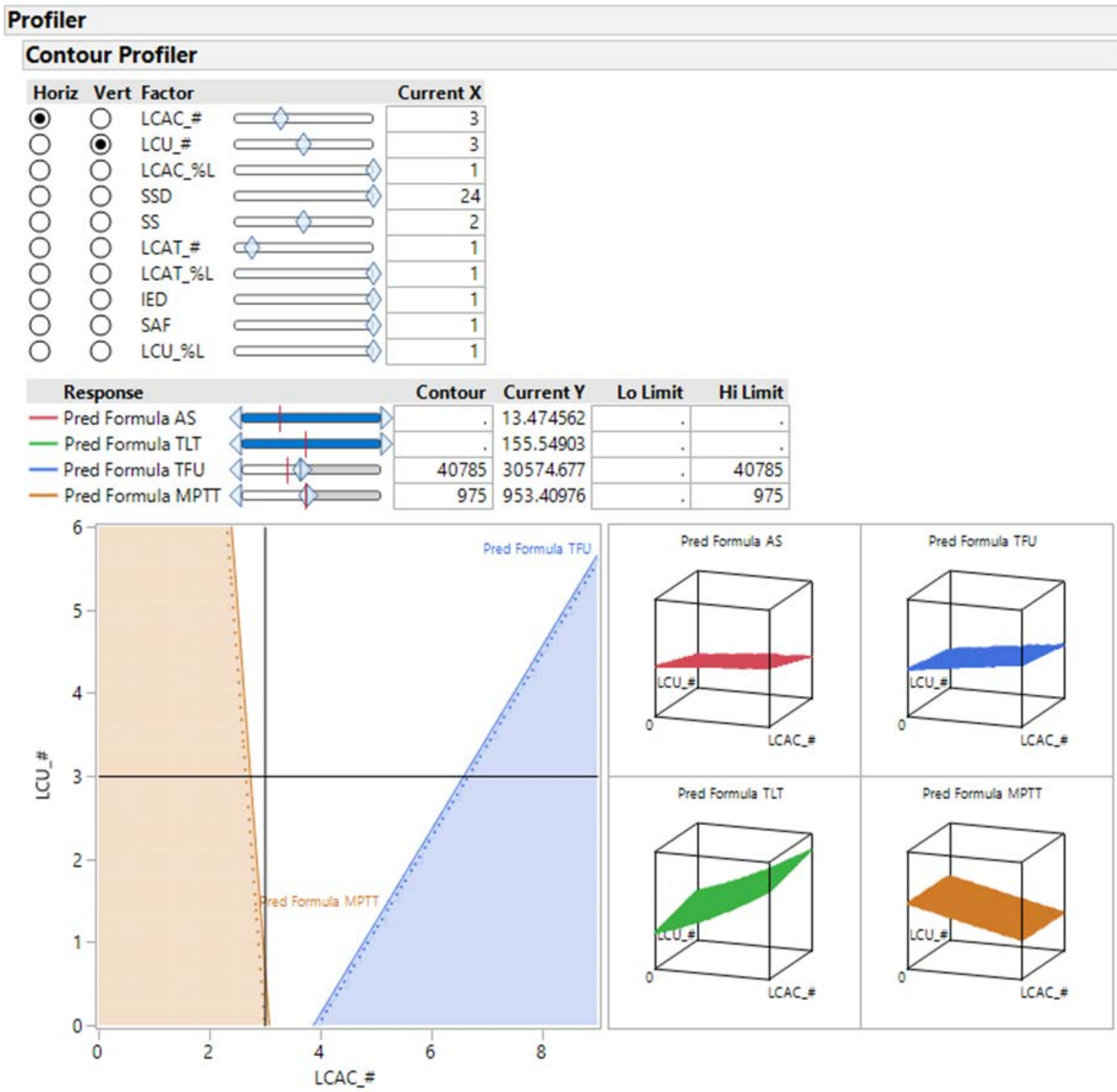

Figure 130. Scenario 16 Solution Space Contour Plot

Scenario #16		
LCU	LCAC	LCAT
3	3	1

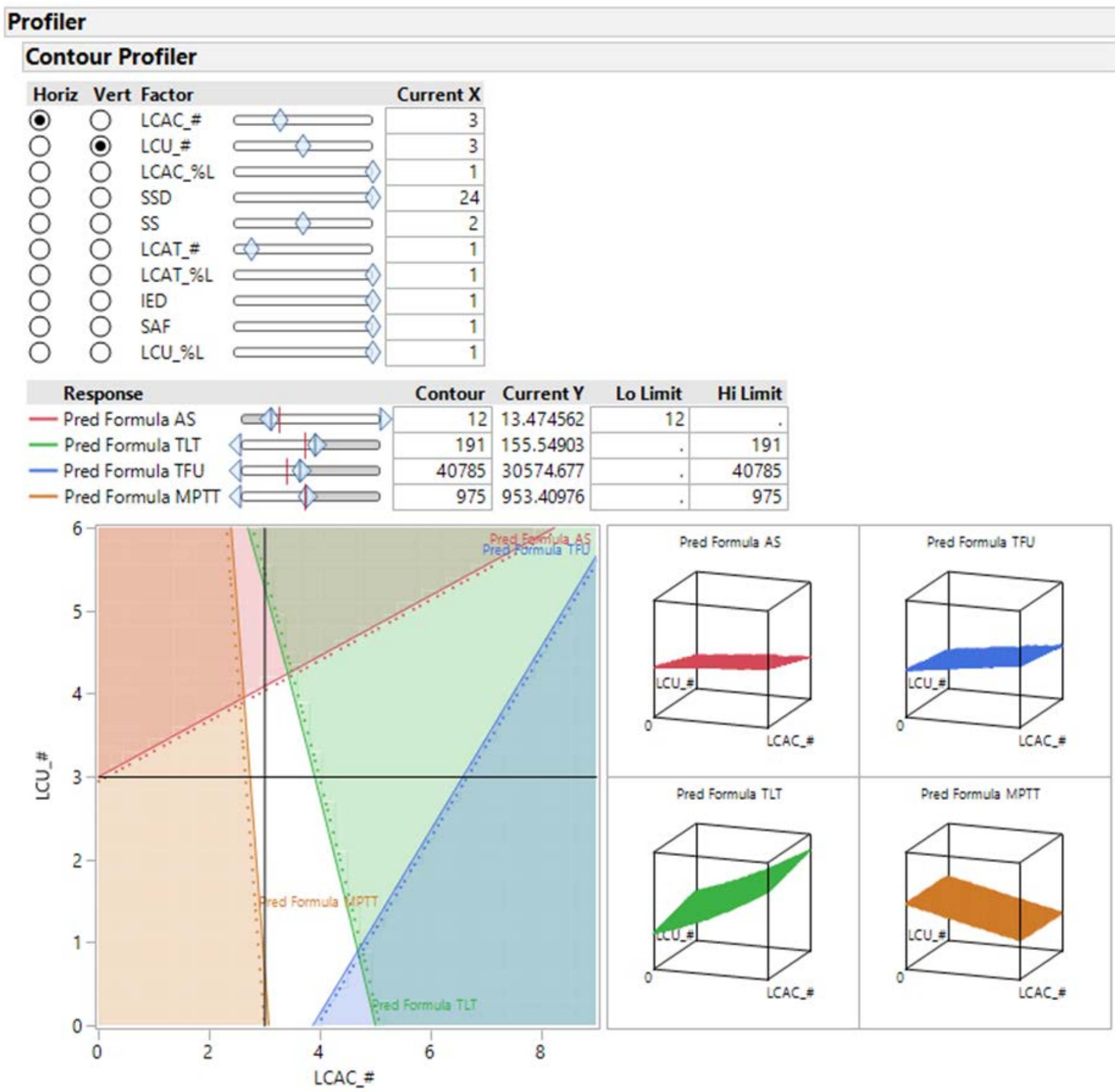

Figure 131. Scenario 16 Solution Space with TLT and AS Contour Plot

Scenario #16		
LCU	LCAC	LCAT
3	3	1

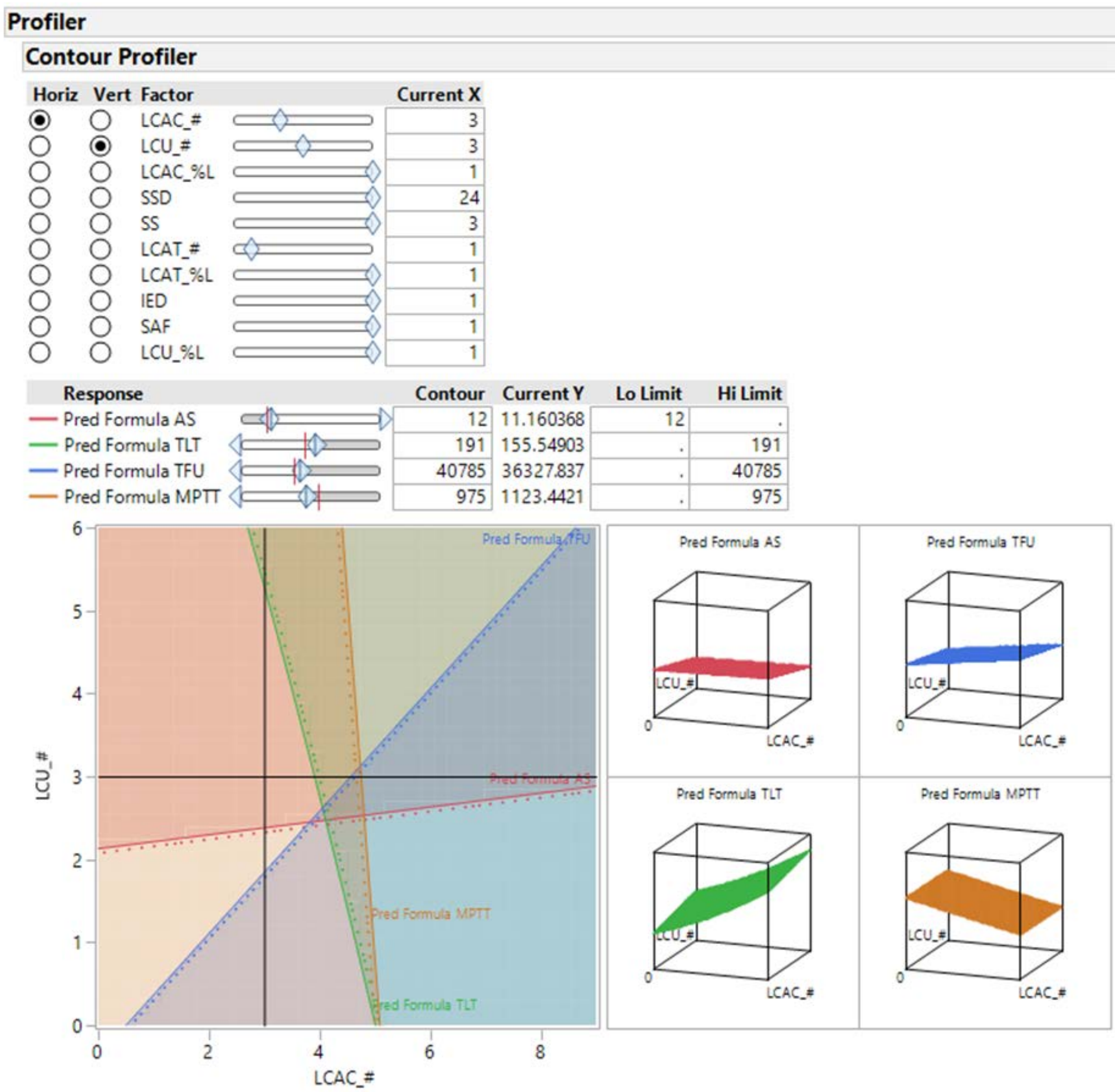

Figure 132. Scenario 16 Limiting Response Contour Plot

Scenario #17		
LCU	LCAC	LCAT
0	7	1

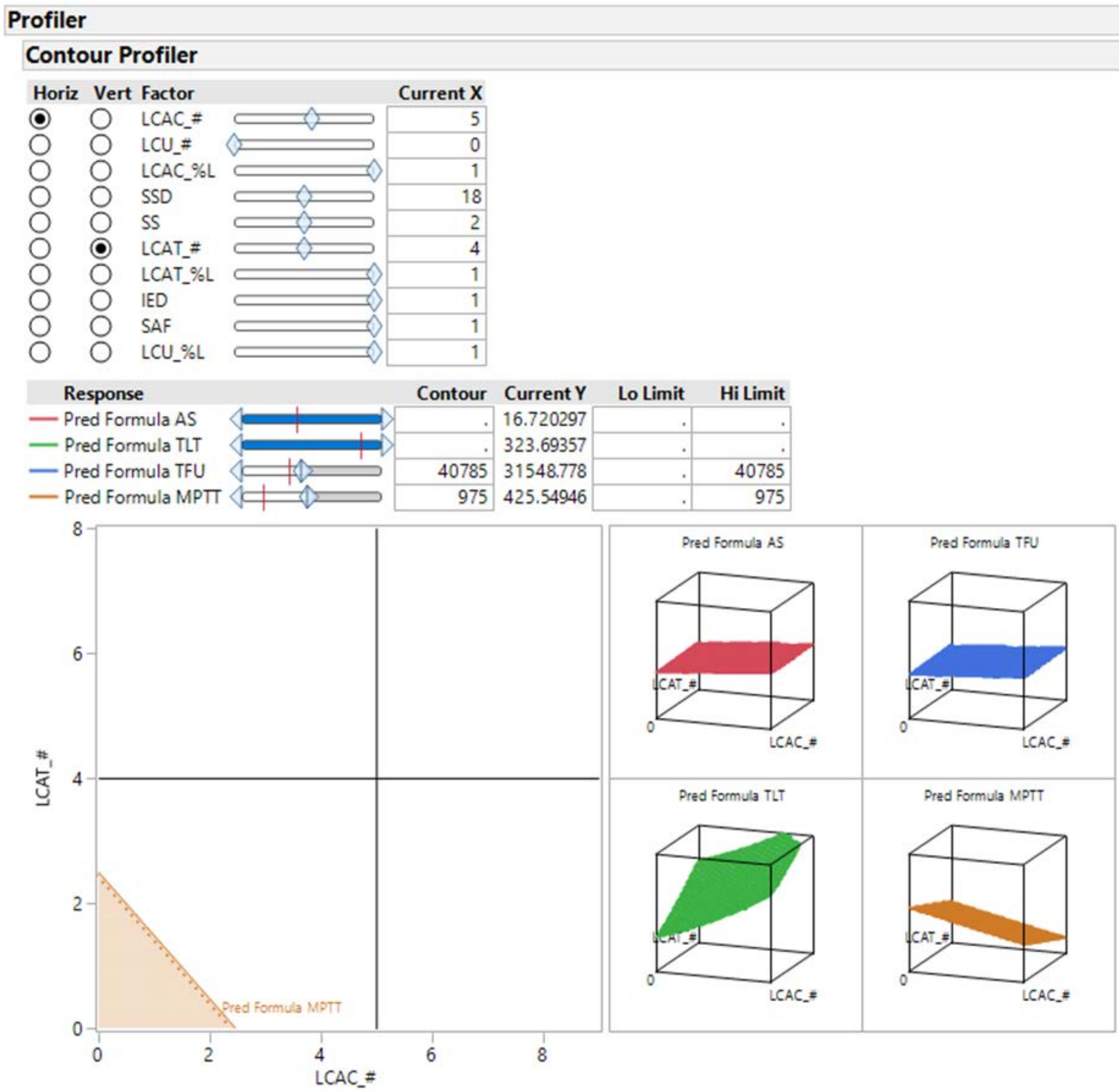

Figure 133. Scenario 17 Solution Space Contour Plot

Scenario #17		
LCU	LCAC	LCAT
0	7	1

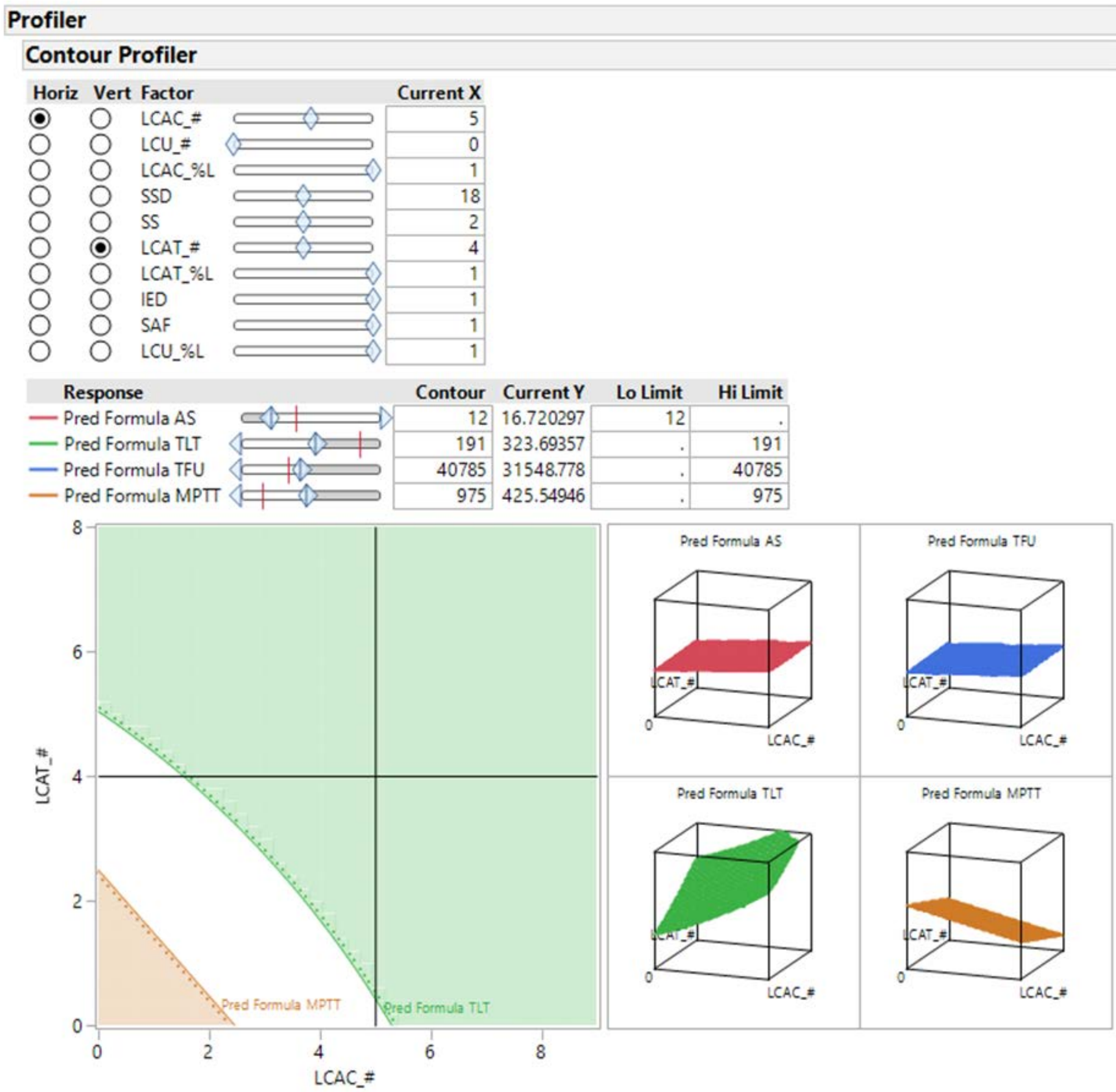

Figure 134. Scenario 17 Solution Space with TLT and AS Contour Plot

Scenario #17		
LCU	LCAC	LCAT
0	7	1

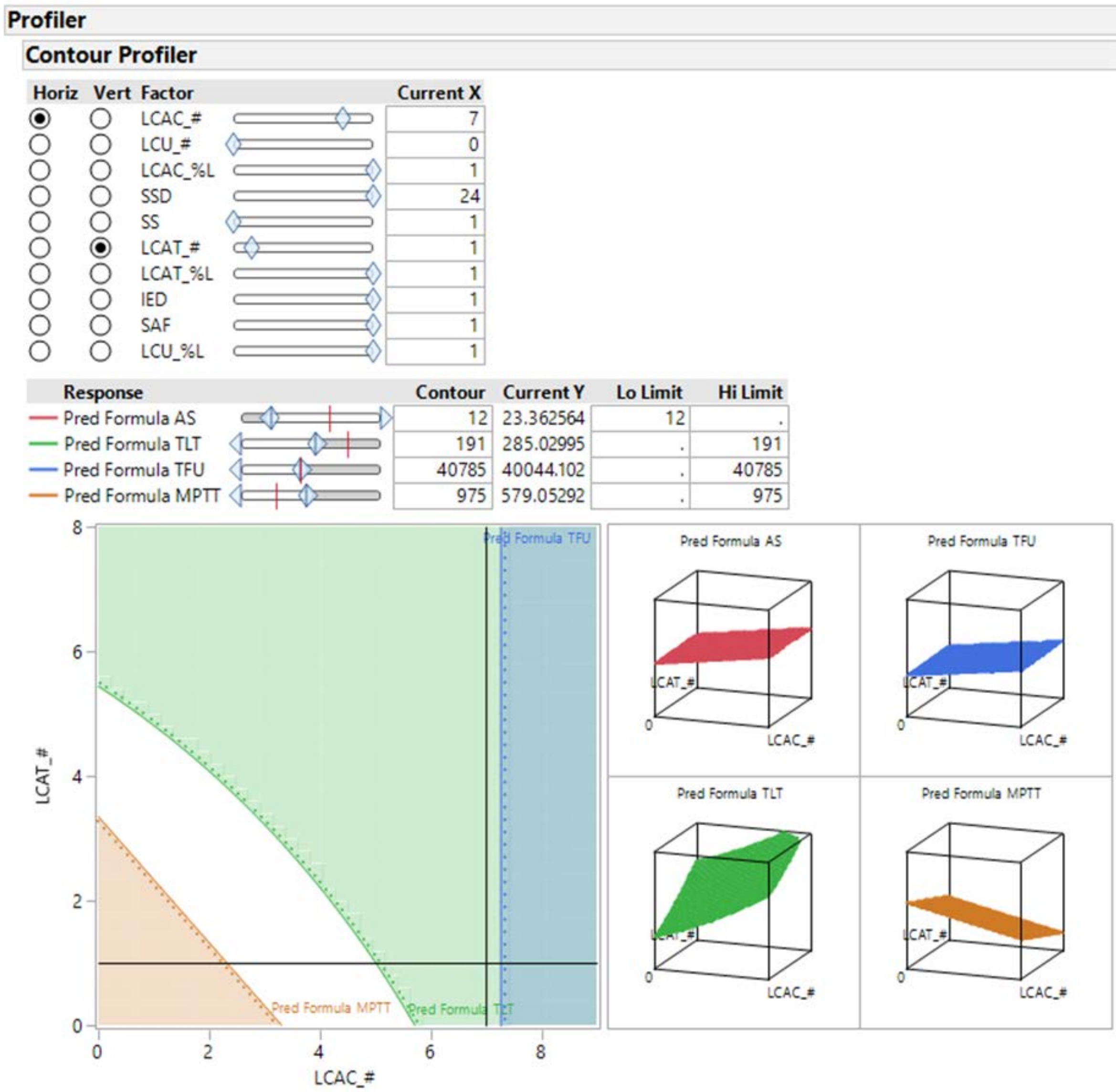

Figure 135. Scenario 17 Solution Space 2 with TLT and AS Contour Plot

Scenario #17		
LCU	LCAC	LCAT
0	7	1

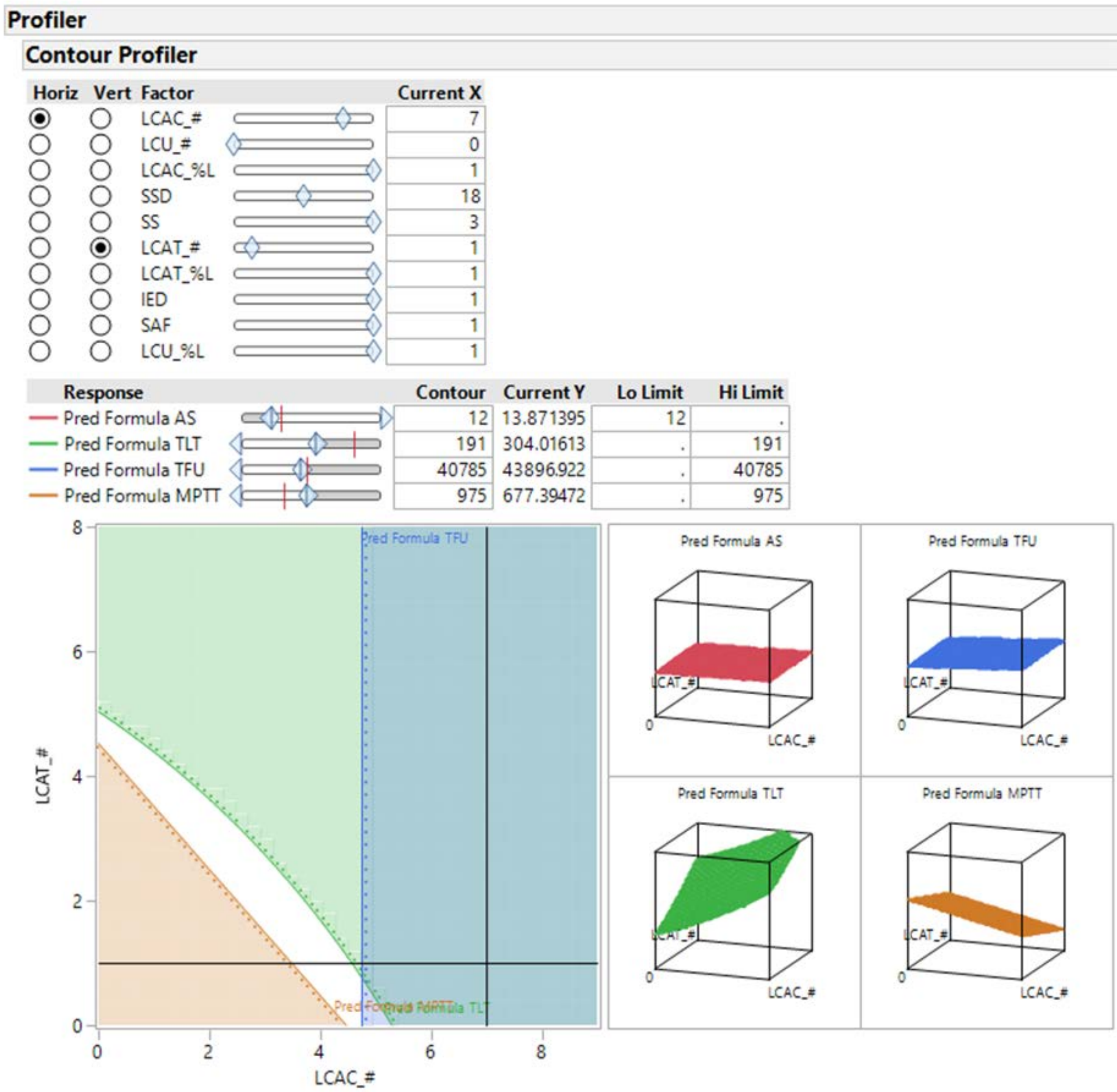

Figure 136. Scenario 17 Limiting Response Contour Plot

Scenario #18		
LCU	LCAC	LCAT
0	3	5

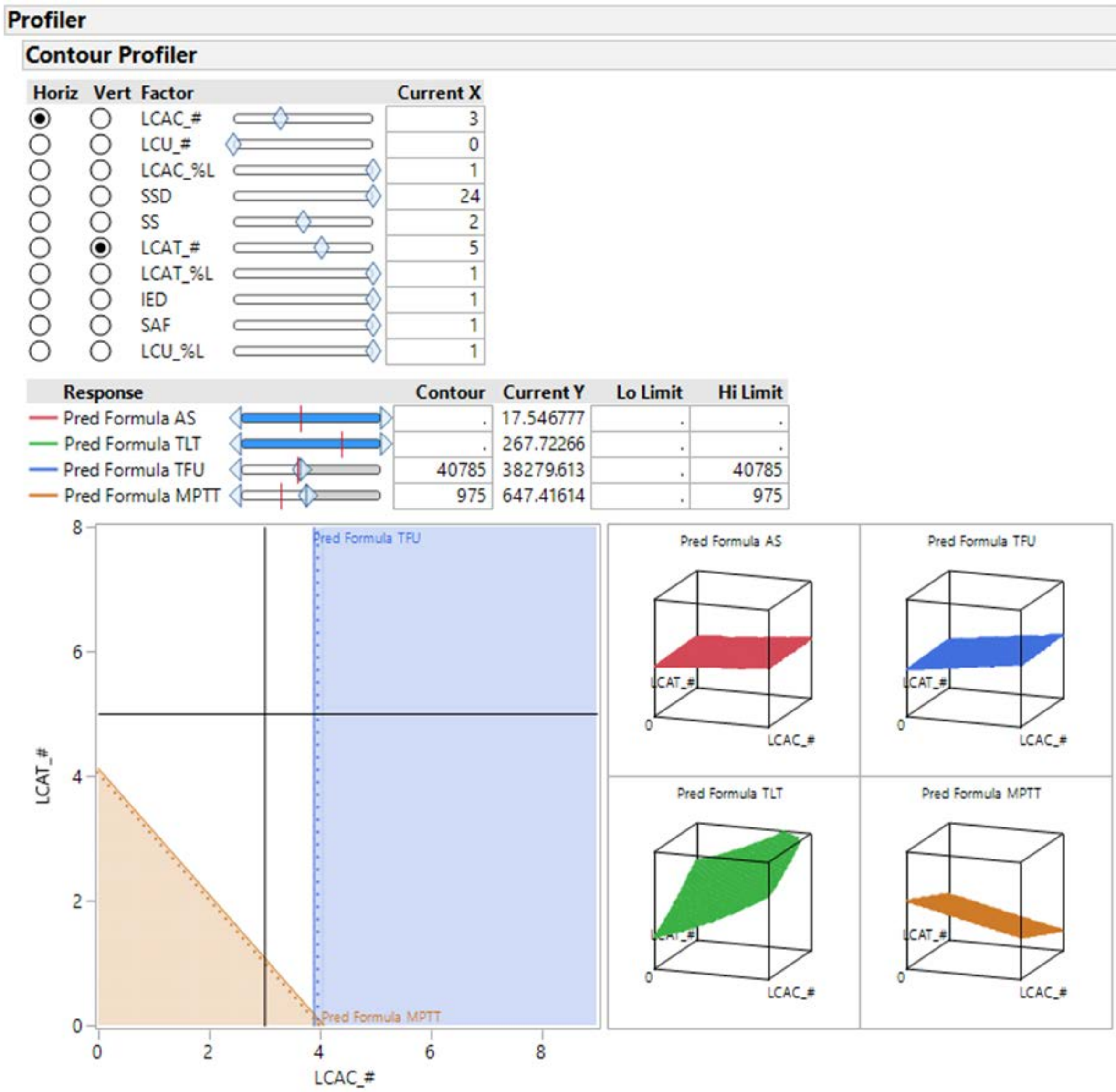

Figure 137. Scenario 18 Solution Space Contour Plot

Scenario #18		
LCU	**LCAC**	**LCAT**
0	3	5

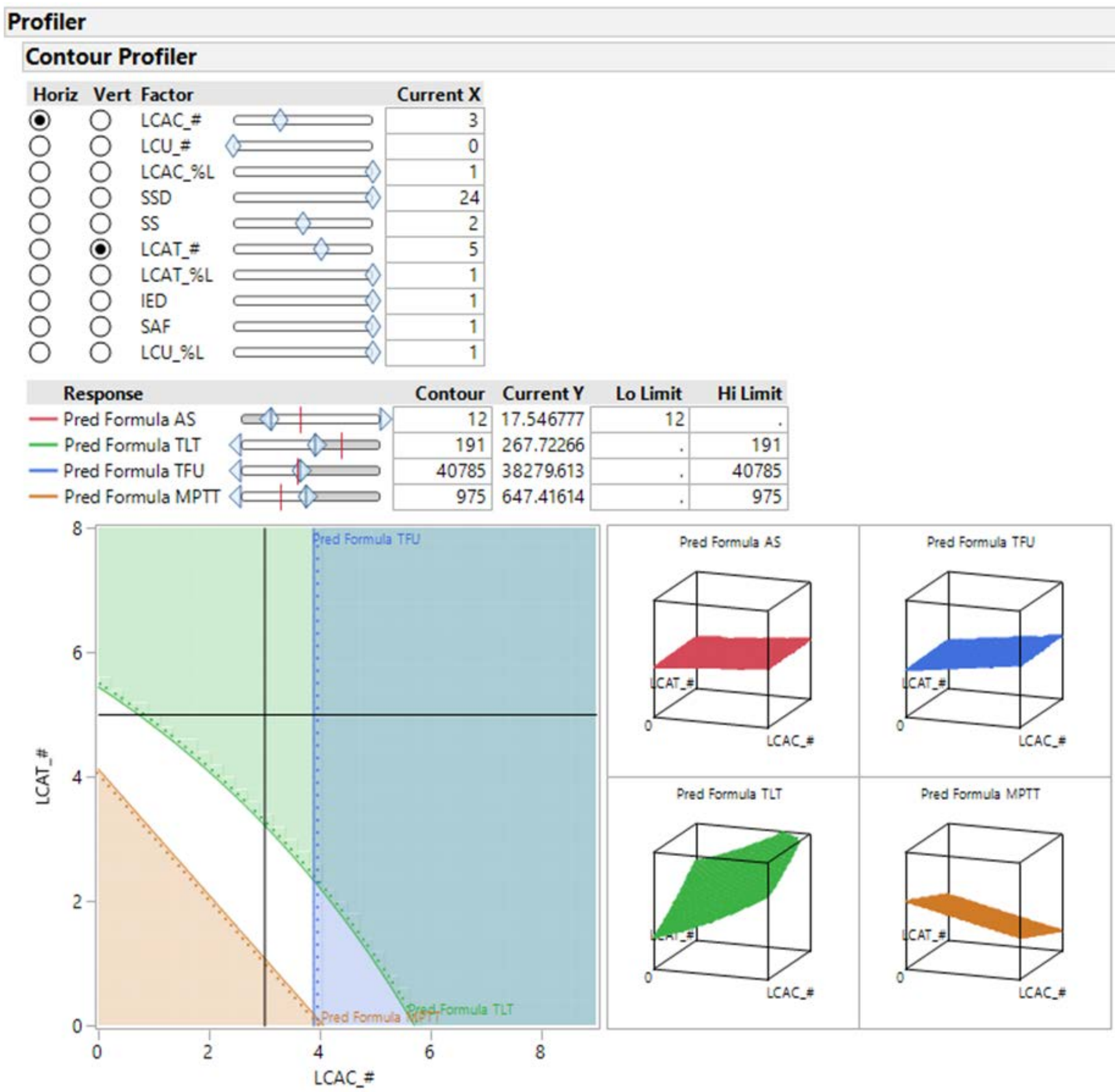

Figure 138. Scenario 18 Solution Space with TLT and AS Contour Plot

Scenario #18		
LCU	LCAC	LCAT
0	3	5

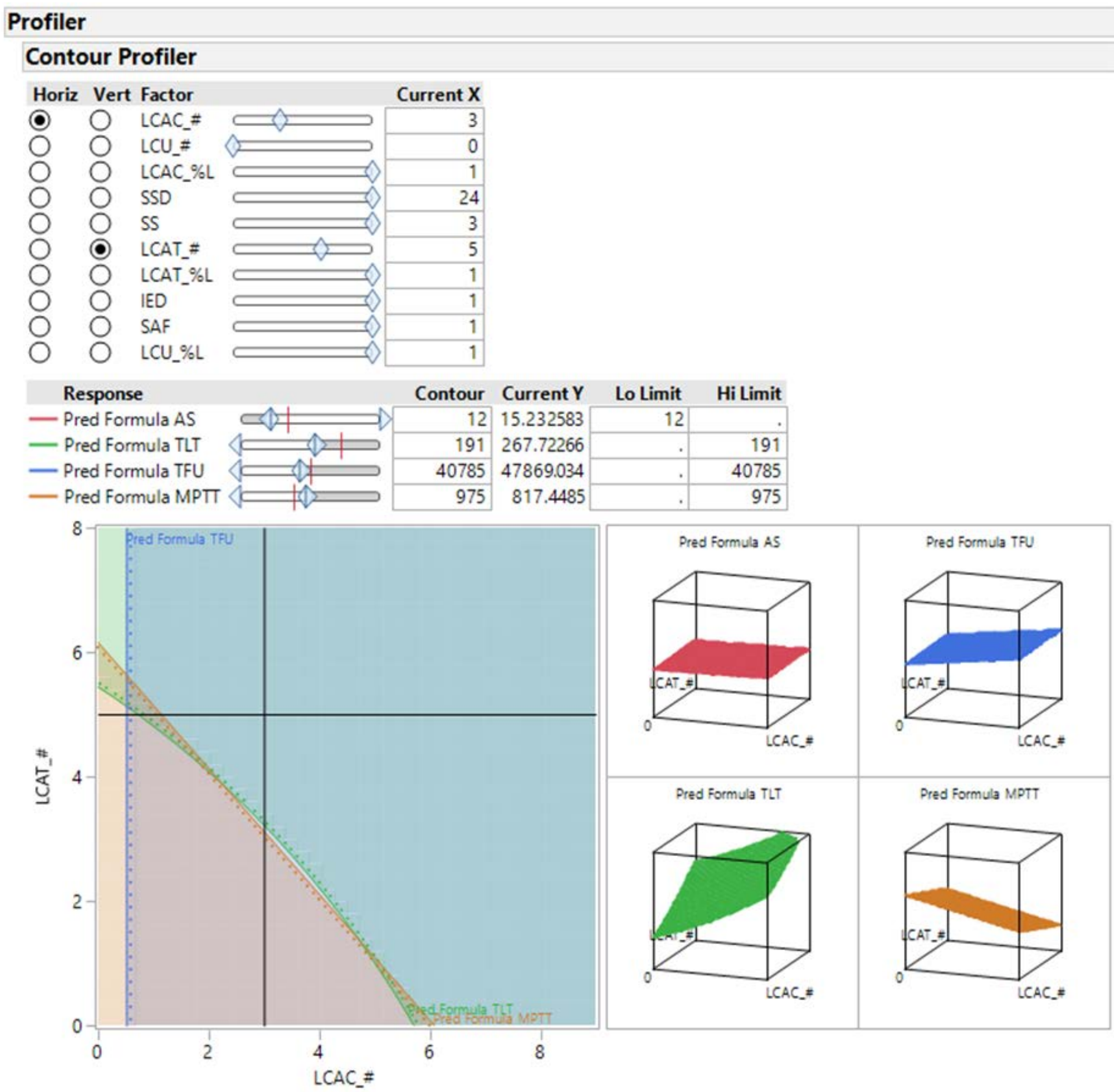

Figure 139. Scenario 18 Limiting Response Contour Plot

Scenario #19		
LCU	LCAC	LCAT
4	0	3

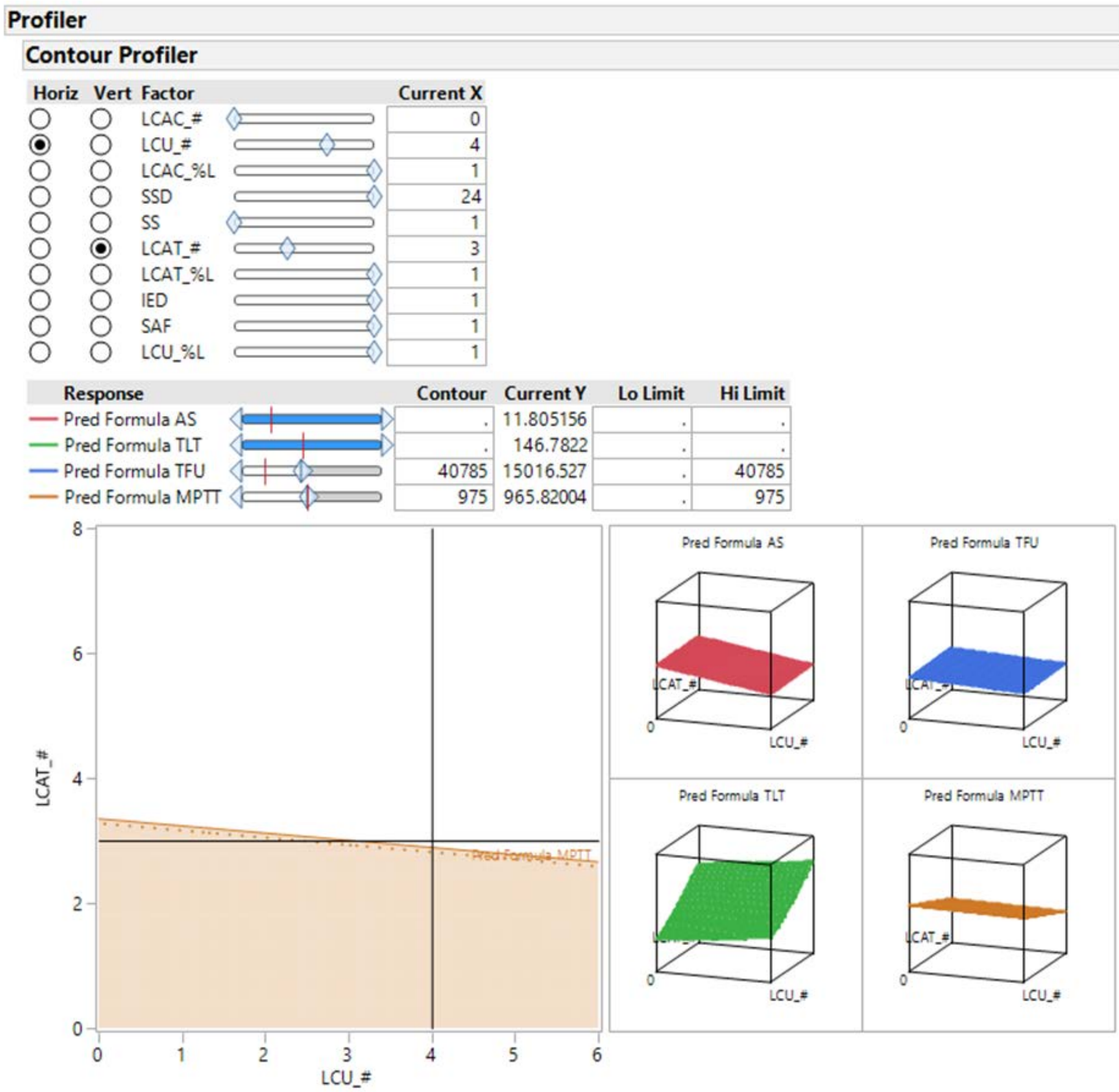

Figure 140. Scenario 19 Solution Space Contour Plot

Scenario #19		
LCU	LCAC	LCAT
4	0	3

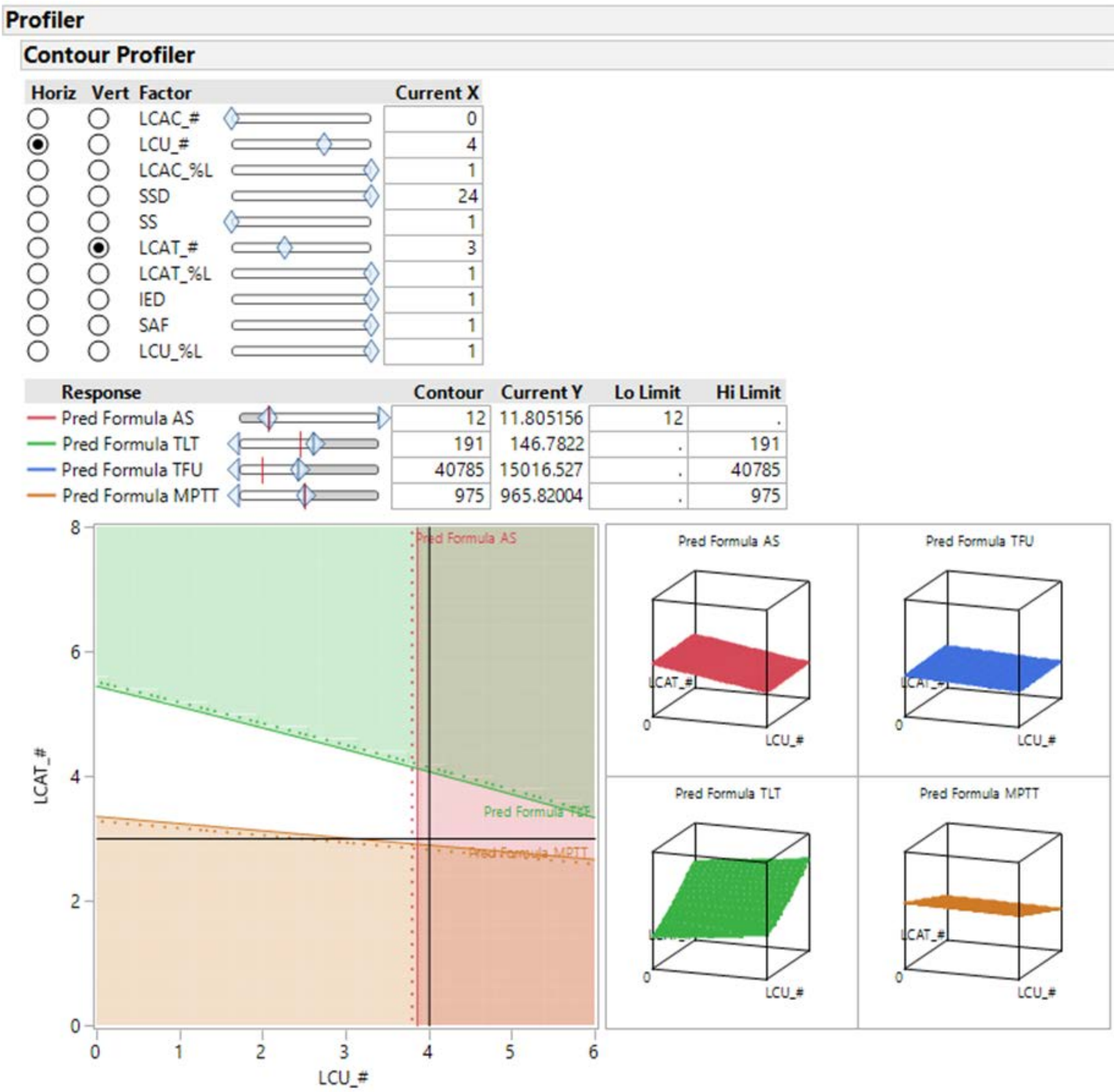

Figure 141. Scenario 19 Solution Space with TLT and AS Contour Plot

Scenario #19		
LCU	LCAC	LCAT
4	0	3

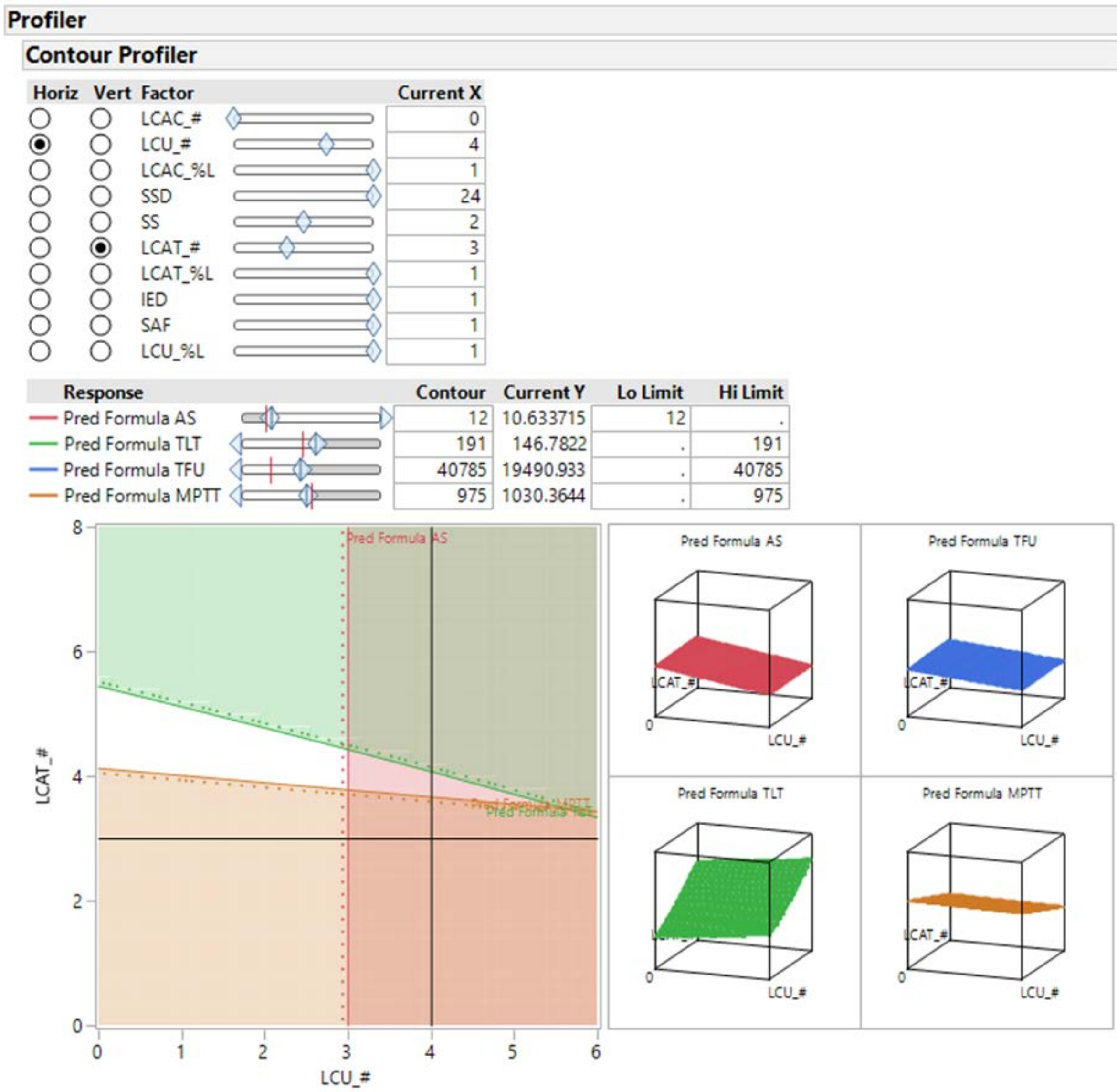

Figure 142. Scenario 19 Limiting Response Contour Plot

Scenario #20		
LCU	LCAC	LCAT
1	4	3

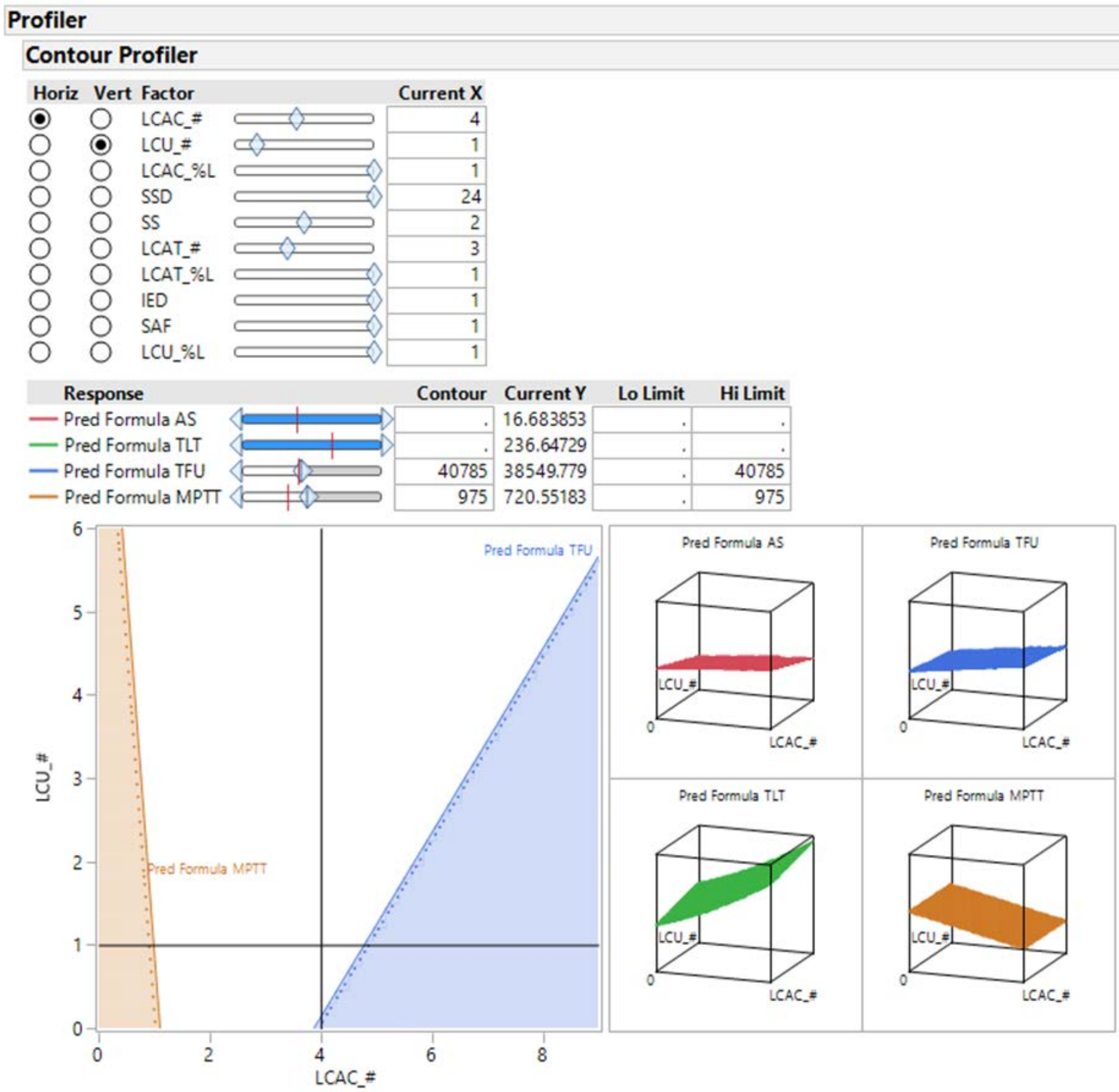

Figure 143. Scenario 20 Solution Space Contour Plot

Scenario #20		
LCU	LCAC	LCAT
1	4	3

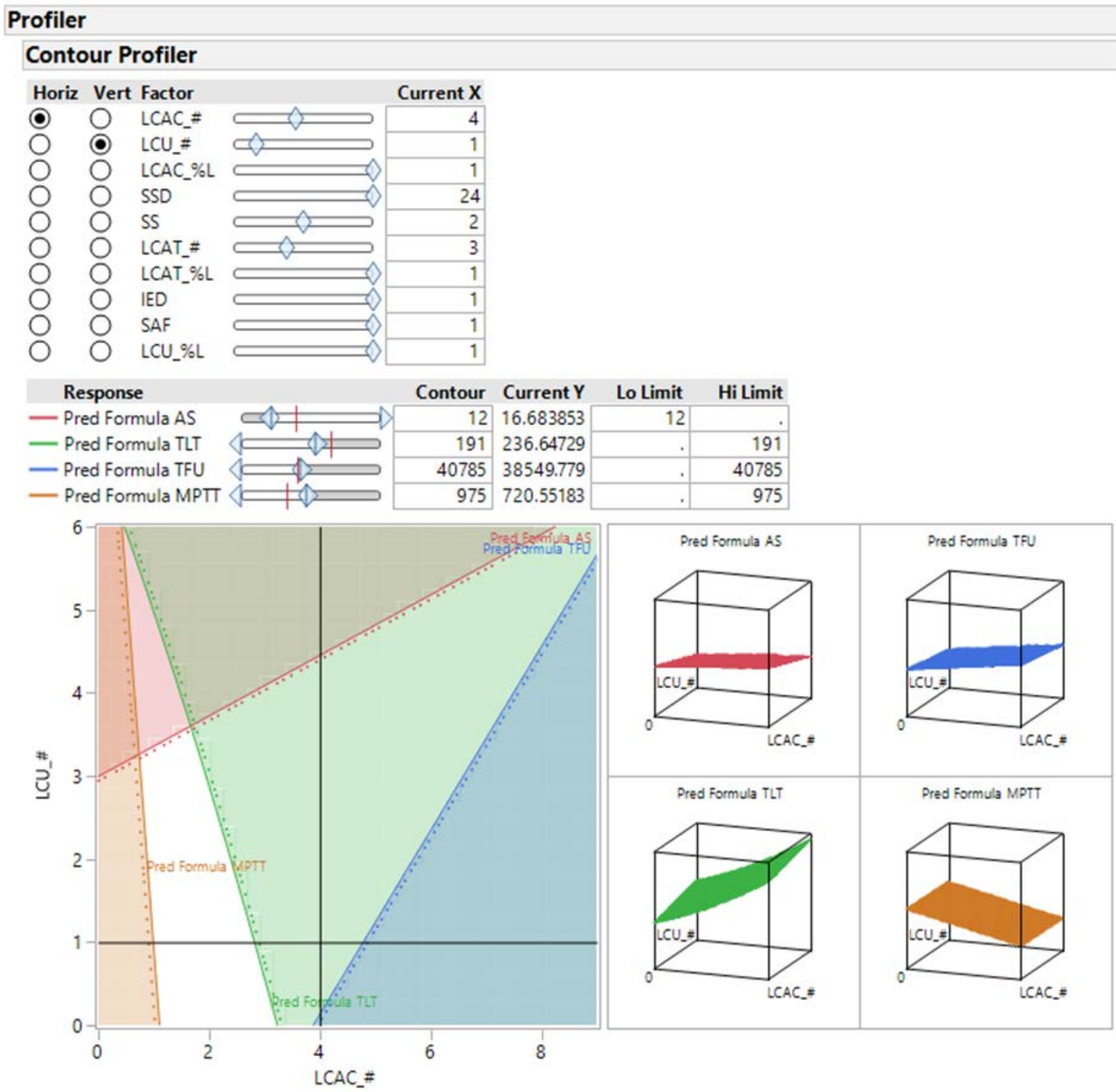

Figure 144. Scenario 20 Solution Space with TLT and AS Contour Plot

Scenario #20		
LCU	LCAC	LCAT
1	4	3

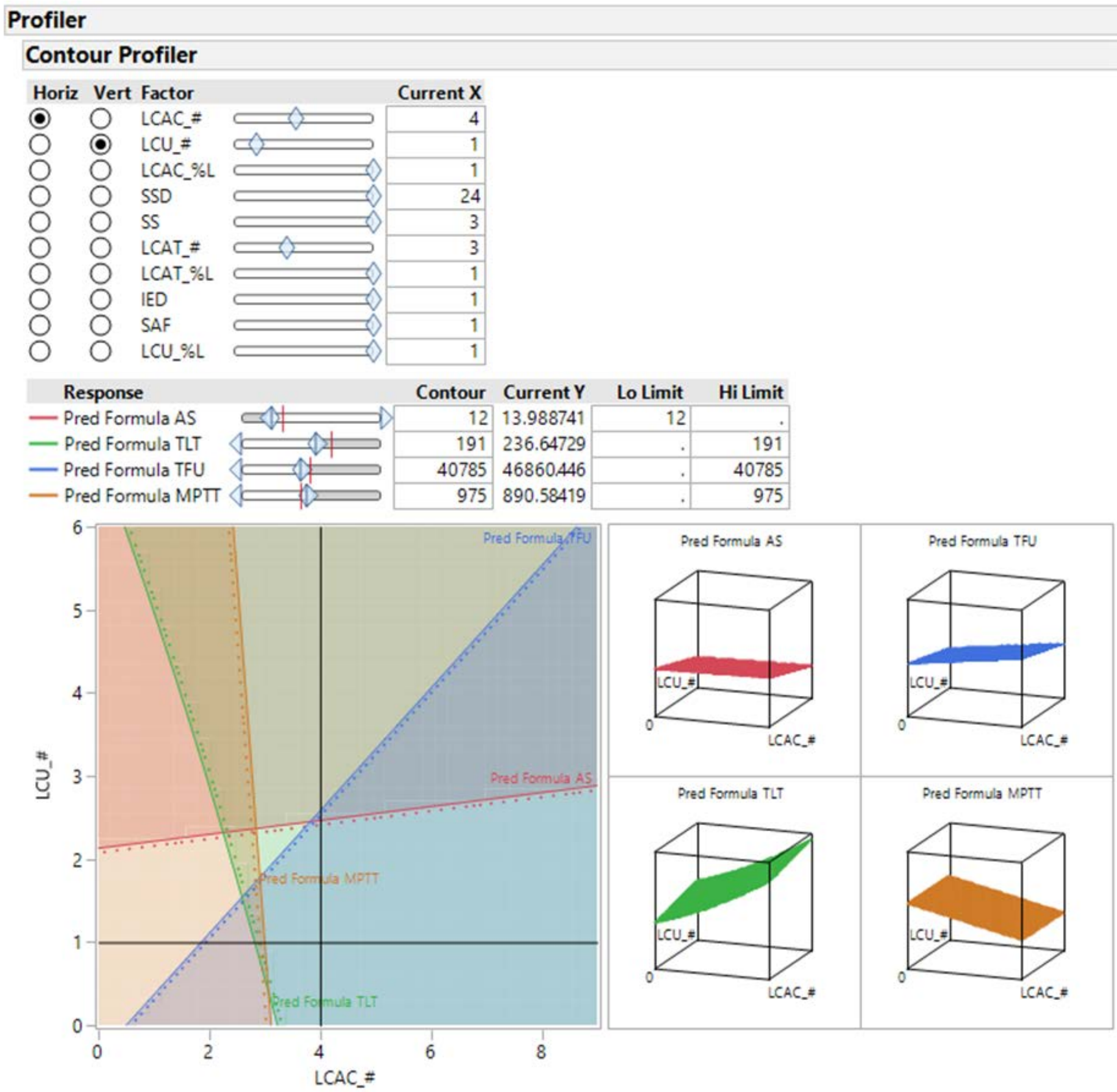

Figure 145. Scenario 20 Limiting Response Contour Plot

Scenario #21		
LCU	LCAC	LCAT
1	0	7

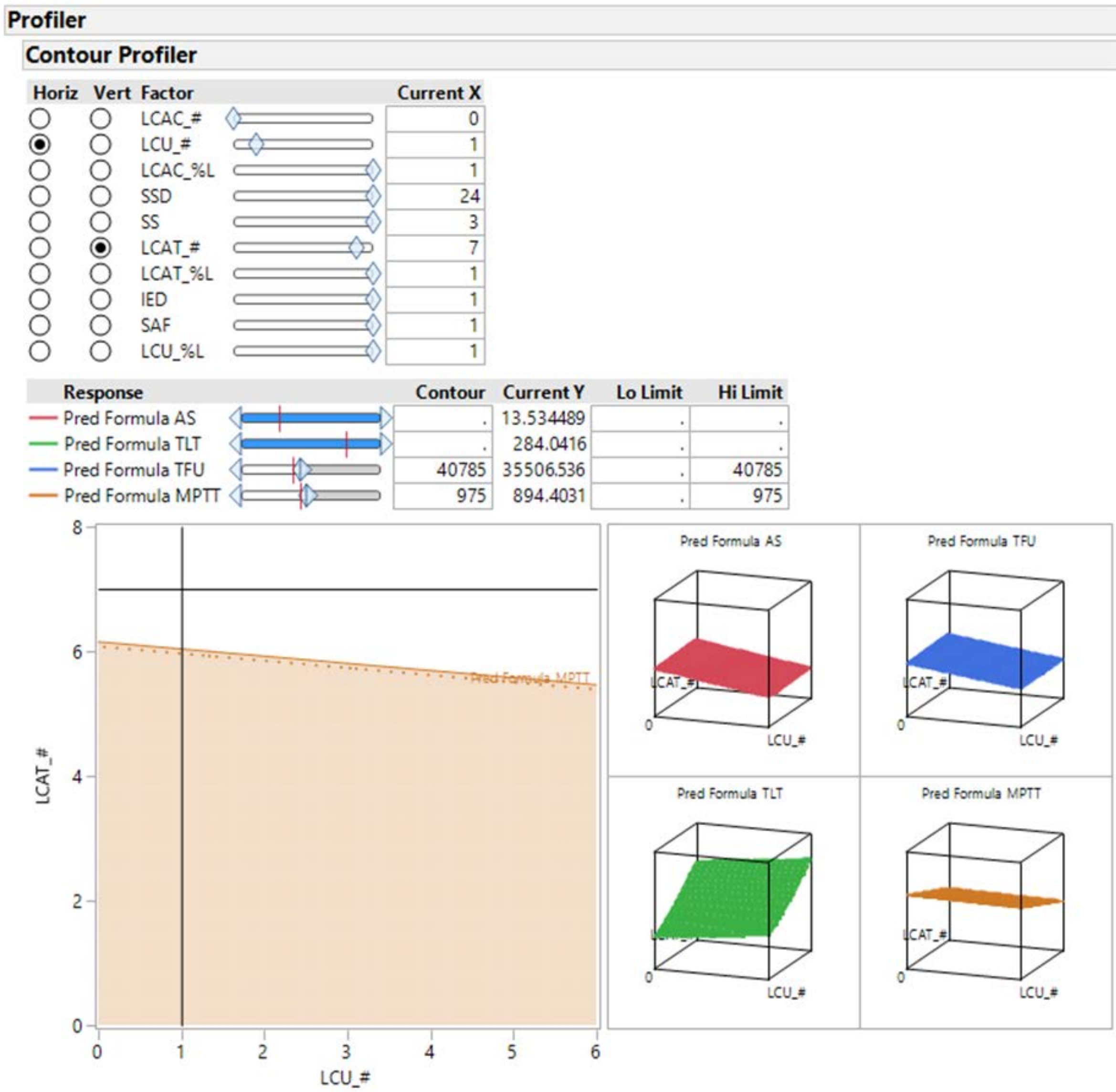

Figure 146. Scenario 21 Solution Space Contour Plot

Scenario #21		
LCU	LCAC	LCAT
1	0	7

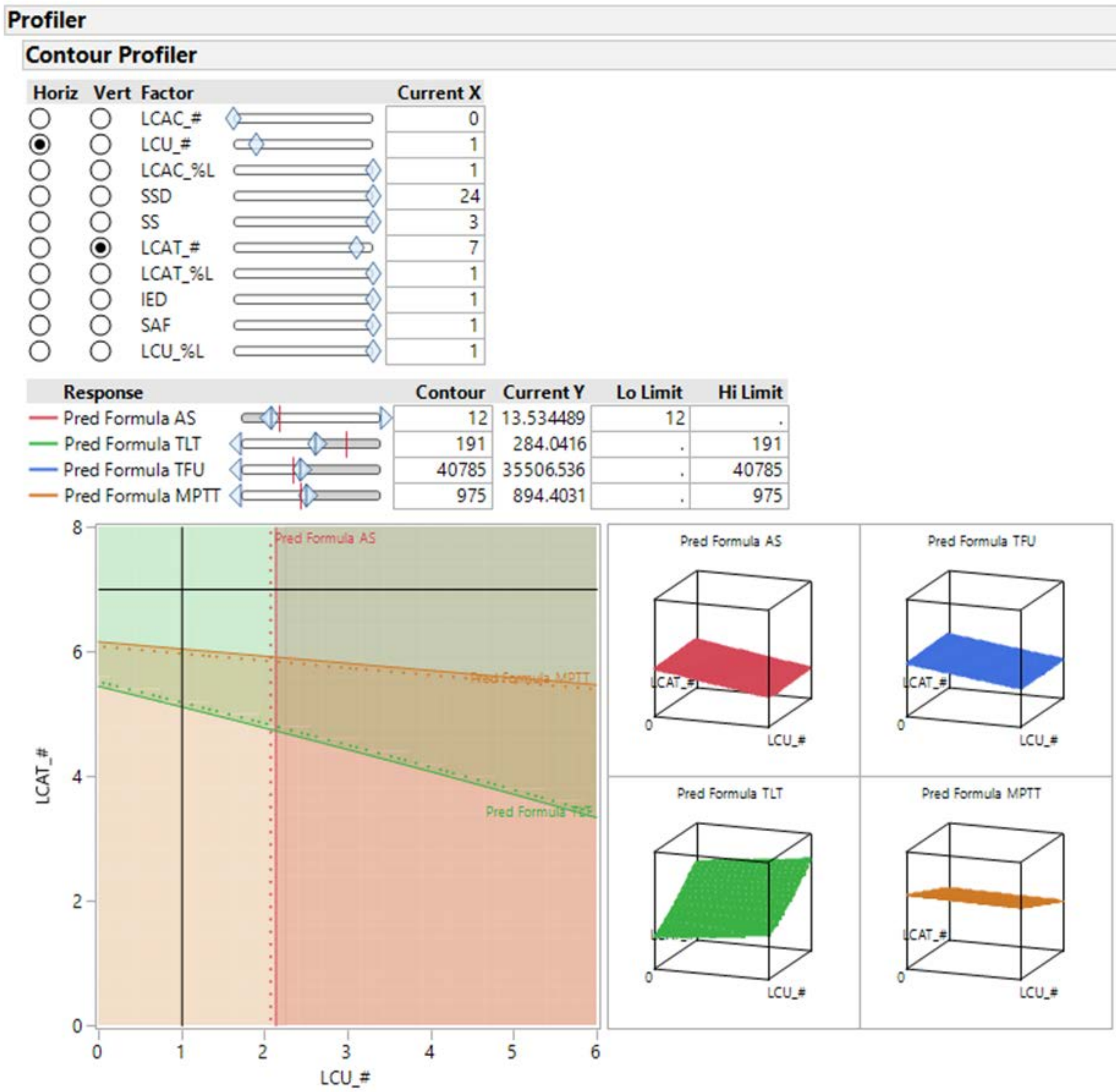

Figure 147. Scenario 21 Solution Space with TLT and AS Contour Plot

Scenario #22		
LCU	**LCAC**	**LCAT**
3	2	3

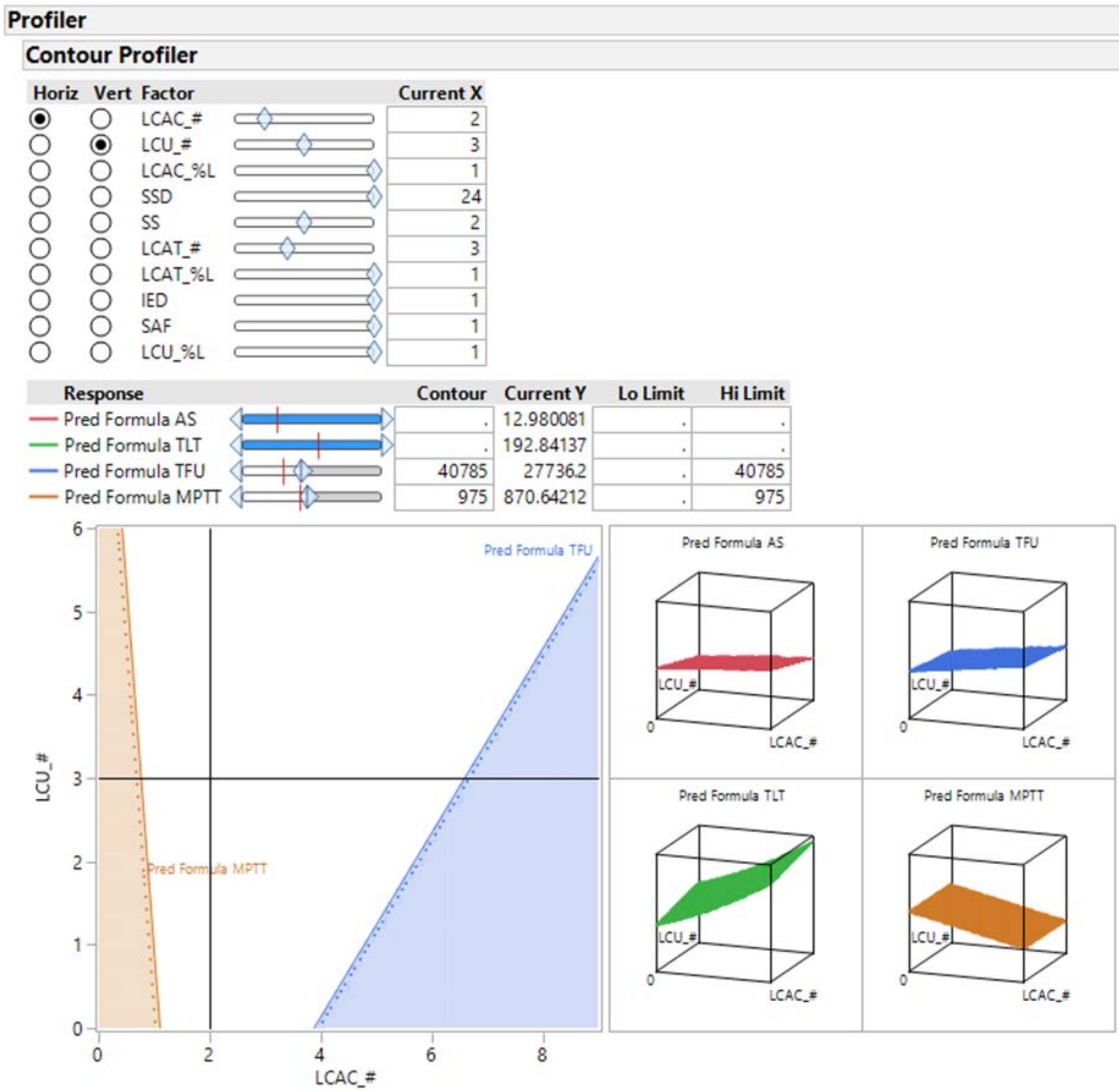

Figure 148. Scenario 22 Solution Space Contour Plot

Scenario #22		
LCU	LCAC	LCAT
3	2	3

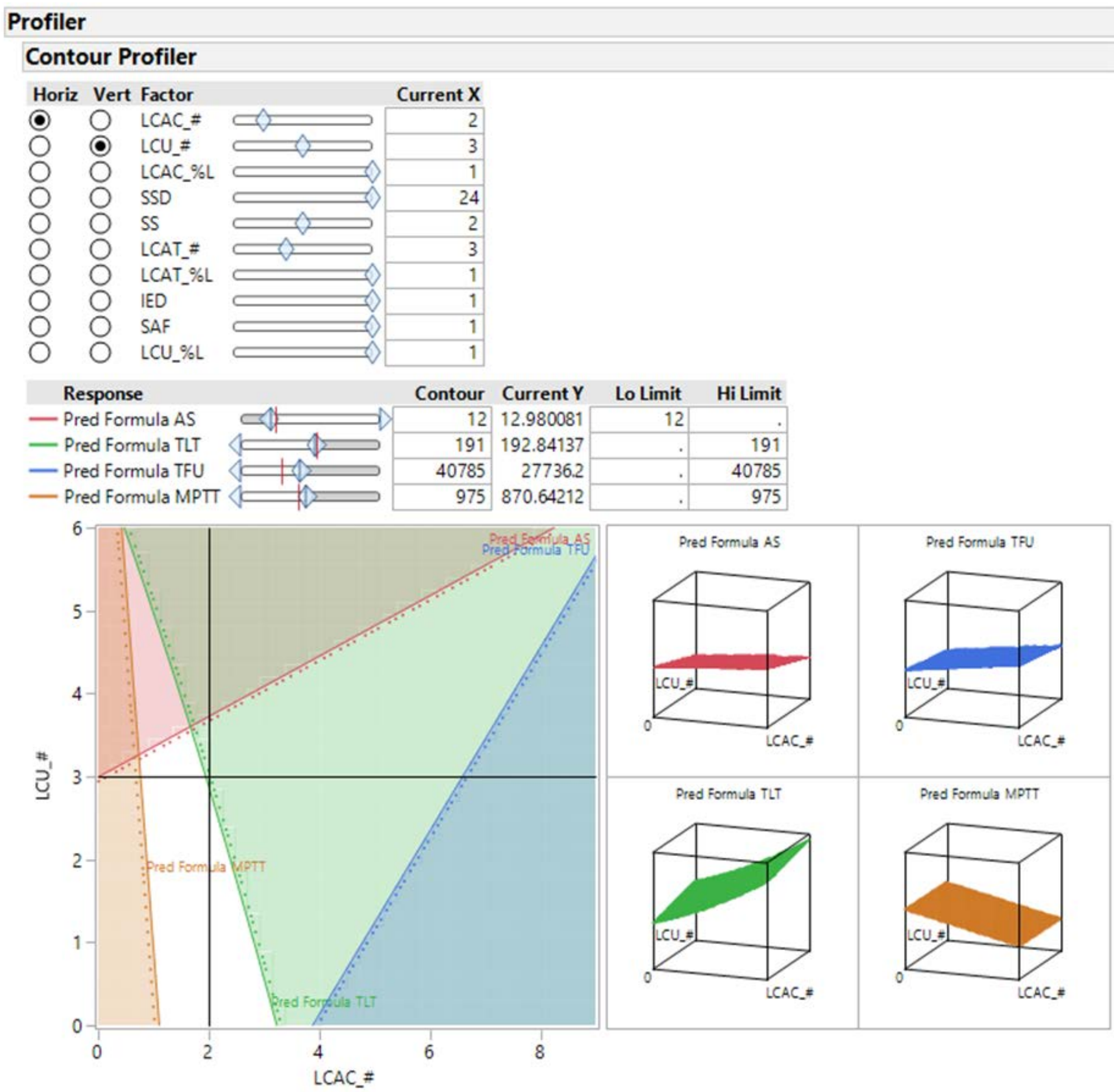

Figure 149. Scenario 22 Solution Space with TLT and AS Contour Plot

Scenario #22		
LCU	LCAC	LCAT
3	2	3

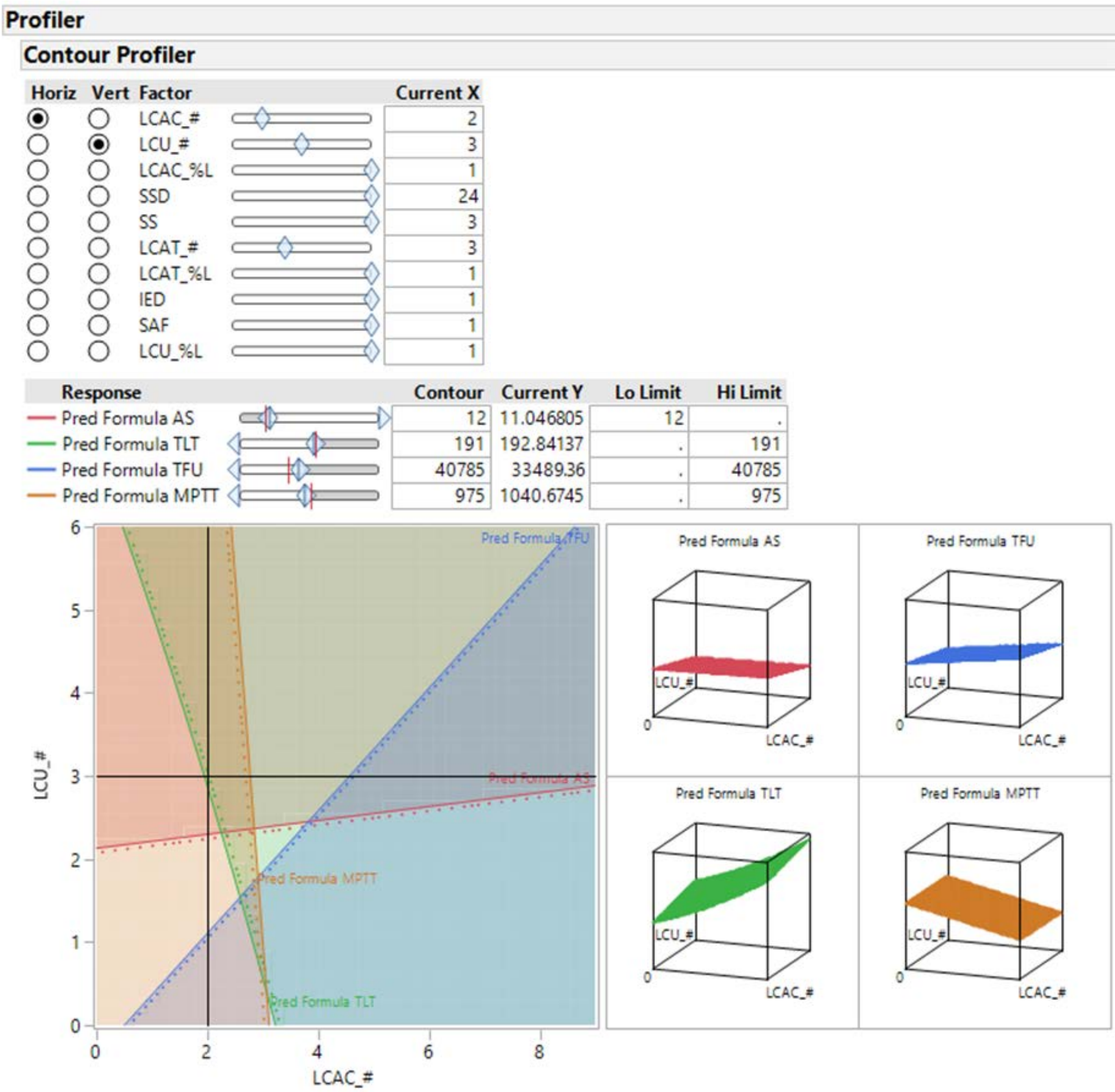

Figure 150. Scenario 22 Limiting Response Contour Plot

Scenario #23		
LCU	LCAC	LCAT
0	6	3

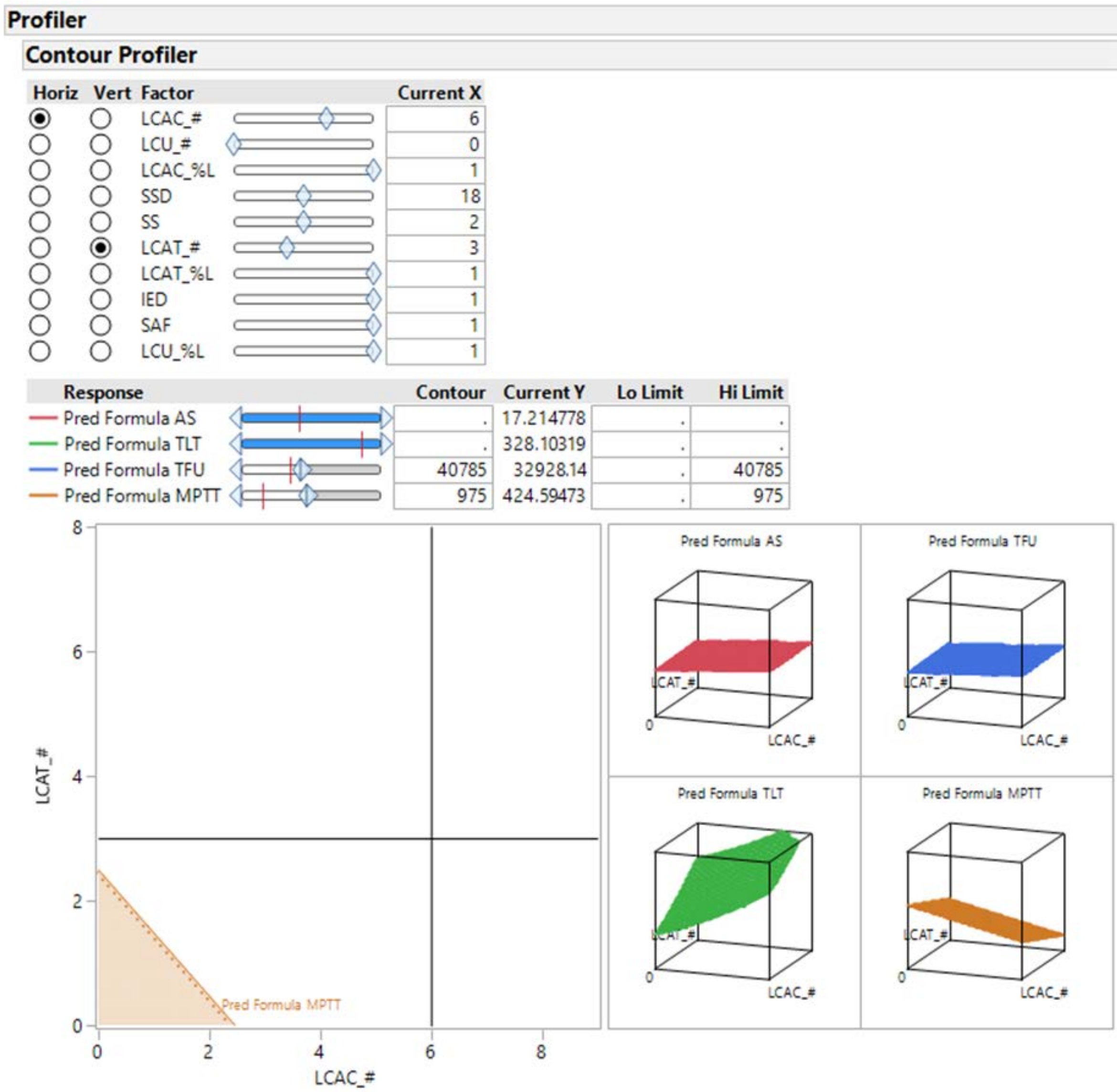

Figure 151. Scenario 23 Solution Space Contour Plot

Scenario #23		
LCU	LCAC	LCAT
0	6	3

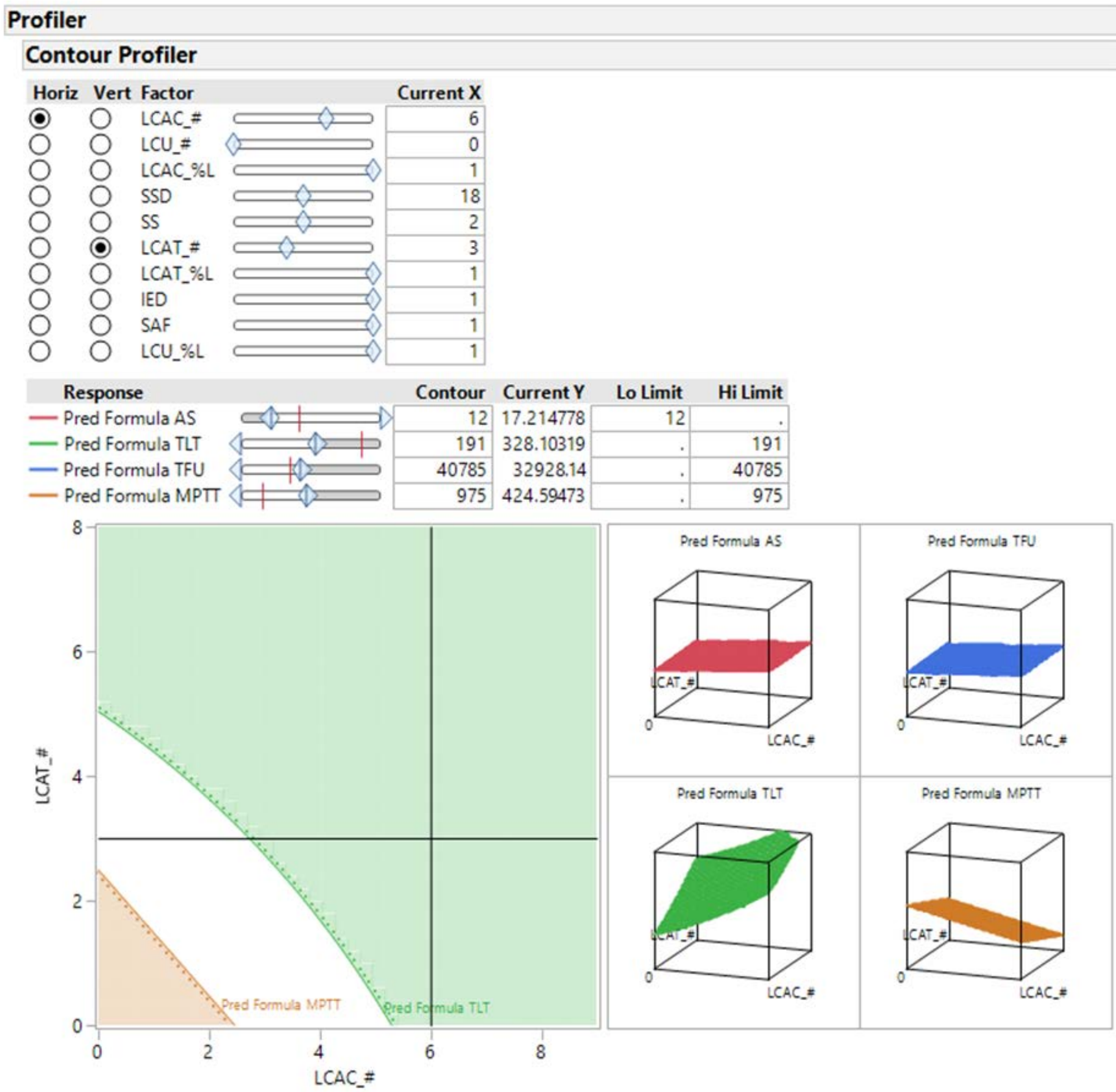

Figure 152. Scenario 23 Solution Space with TLT and AS Contour Plot

Scenario #23		
LCU	LCAC	LCAT
0	6	3

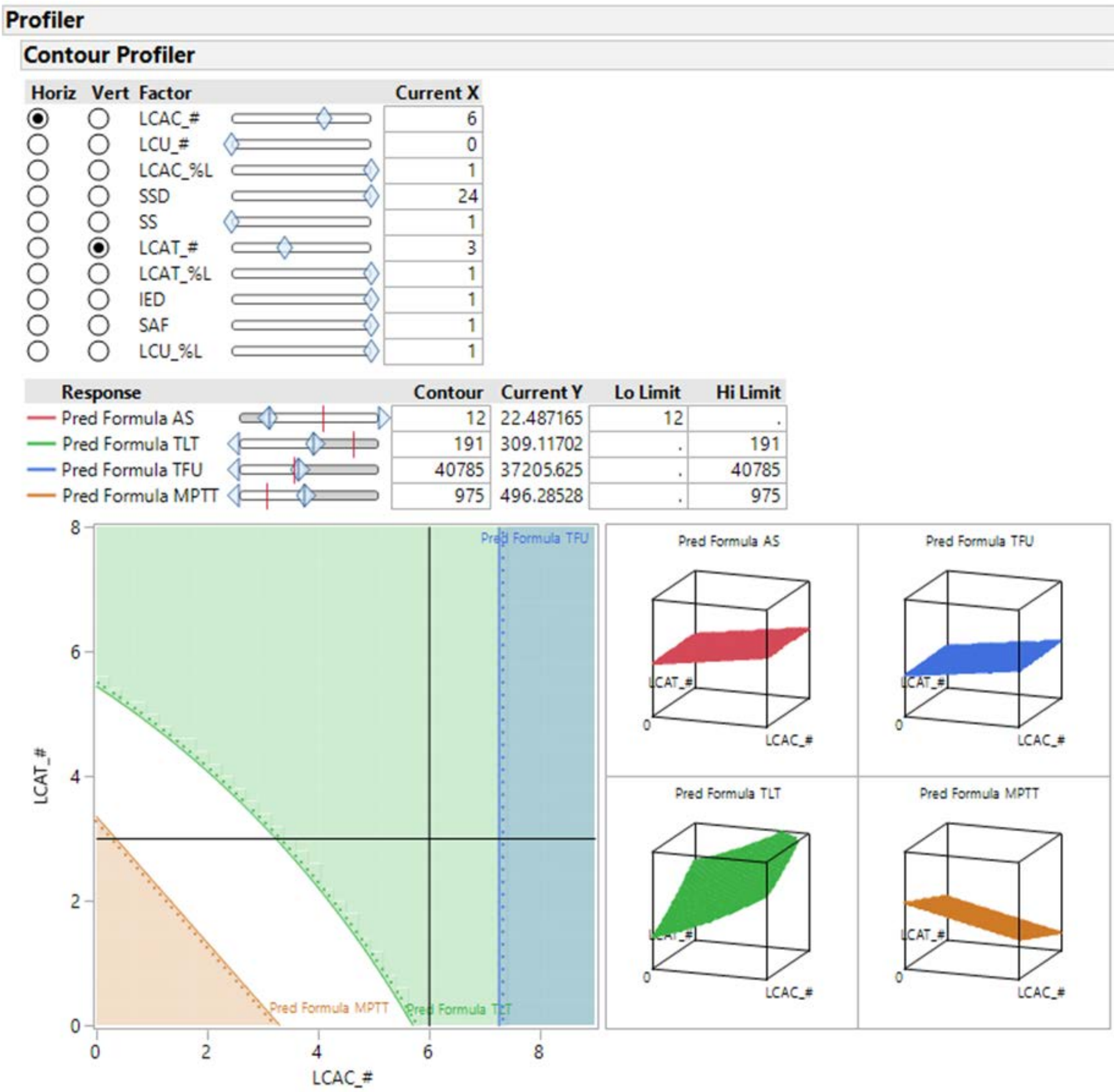

Figure 153. Scenario 23 Solution Space 2 with TLT and AS Contour Plot

Scenario #23		
LCU	LCAC	LCAT
0	6	3

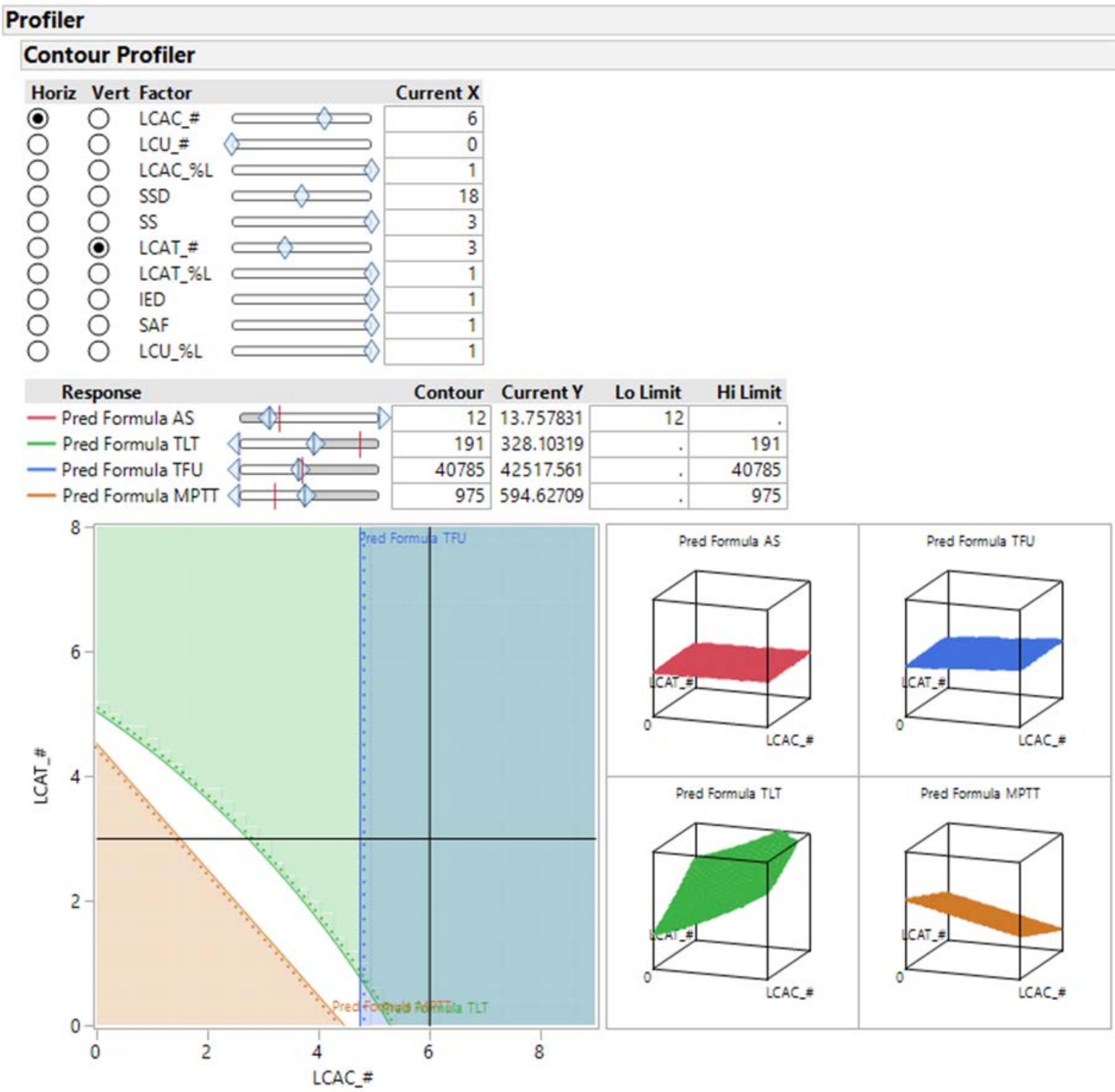

Figure 154. Scenario 23 Limiting Response Contour Plot

Scenario #24		
LCU	LCAC	LCAT
0	2	7

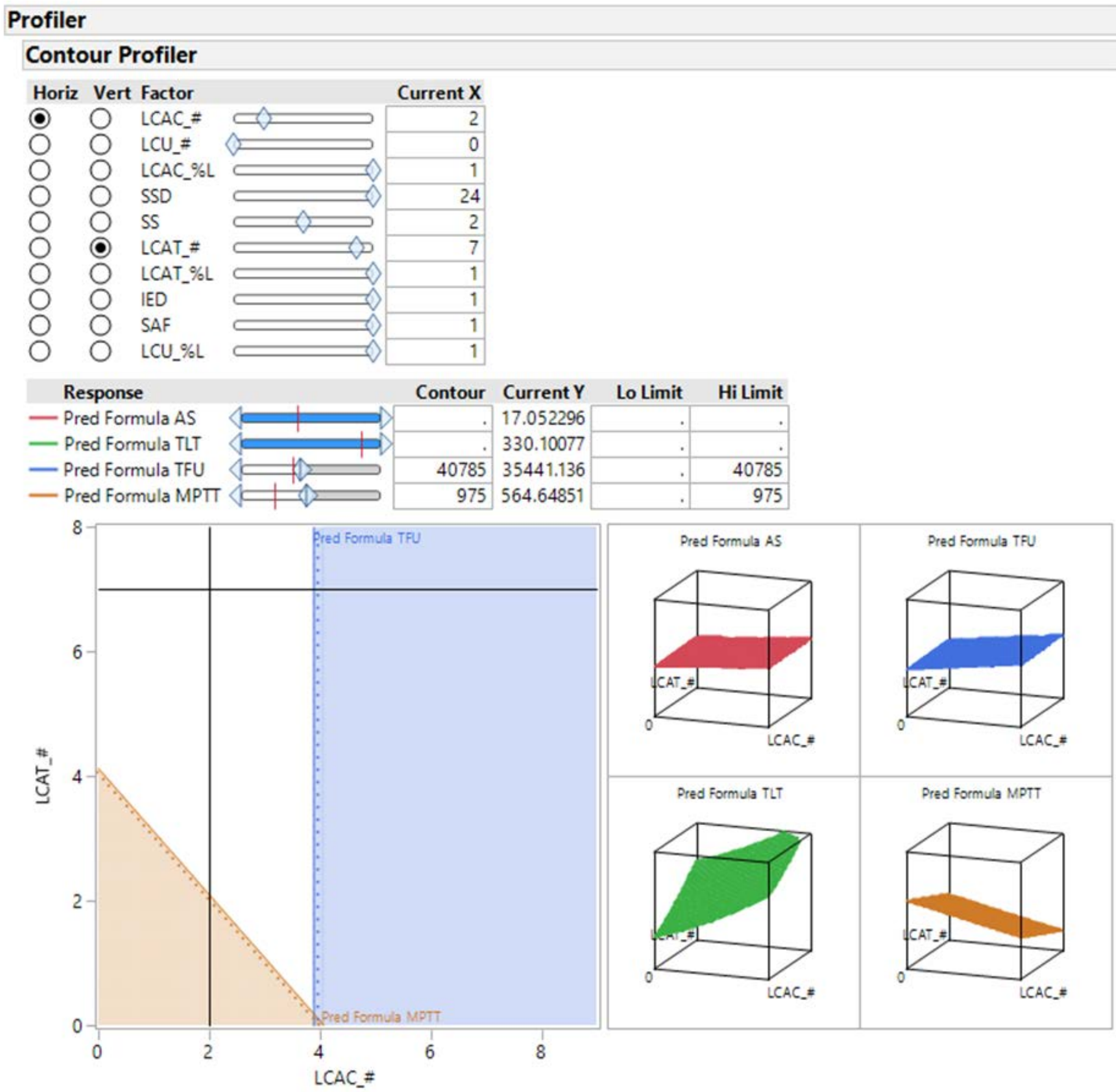

Figure 155. Scenario 24 Solution Space Contour Plot

Scenario #24		
LCU	LCAC	LCAT
0	2	7

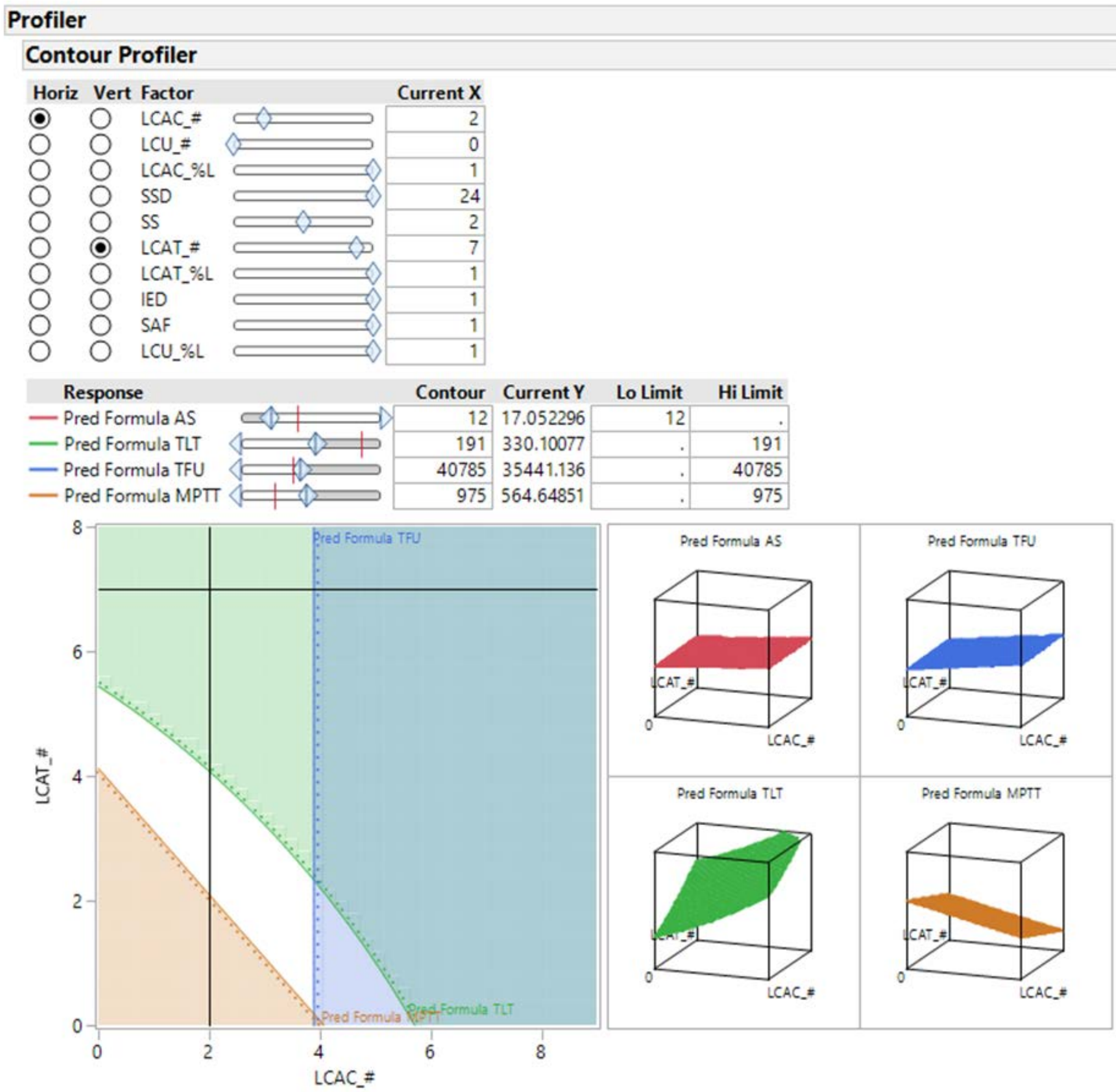

Figure 156. Scenario 24 Solution Space with TLT and AS Contour Plot

Scenario #24		
LCU	LCAC	LCAT
0	2	7

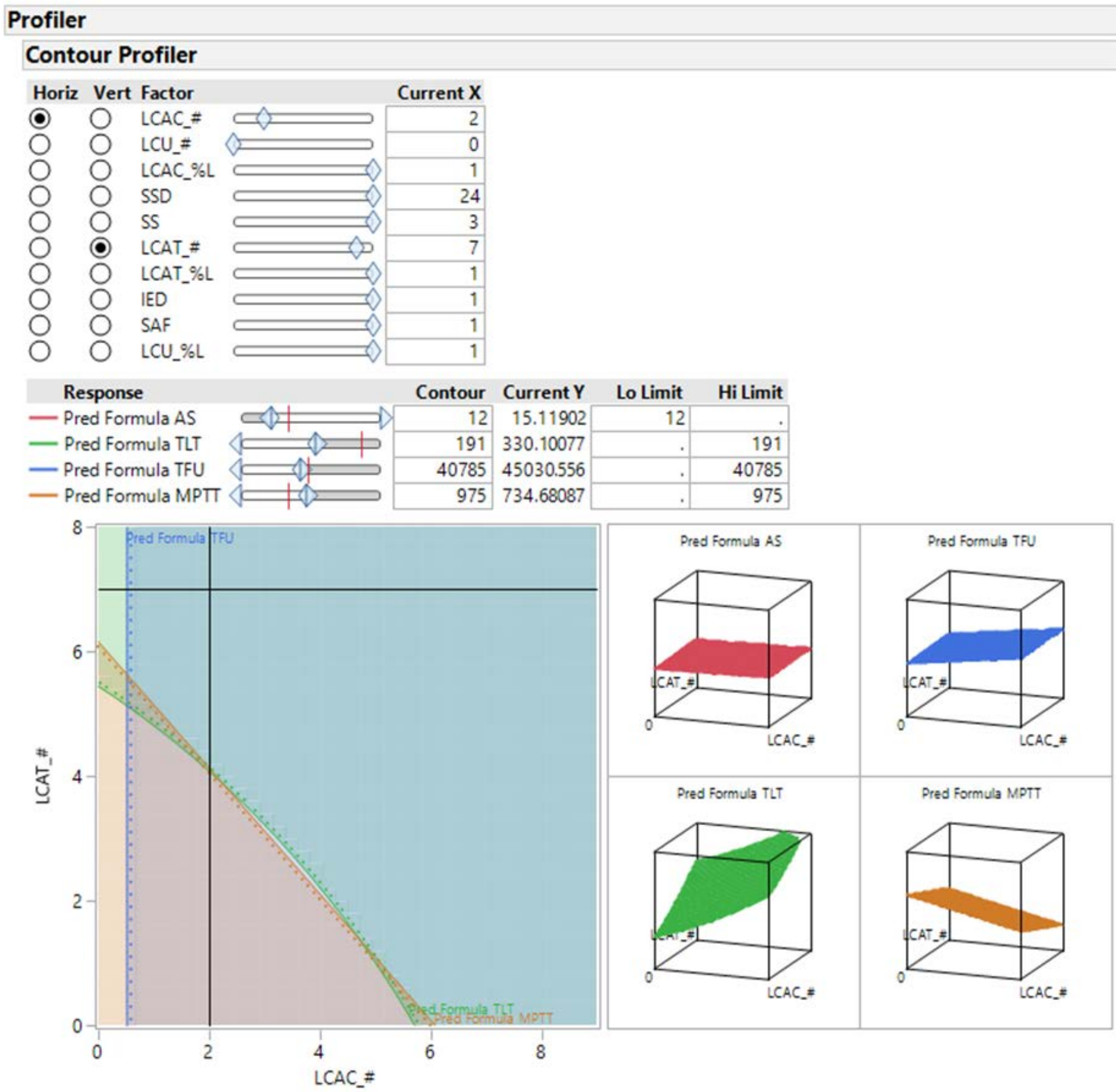

Figure 157. Scenario 24 Limiting Response Contour Plot

Scenario #25		
LCU	LCAC	LCAT
3	0	4

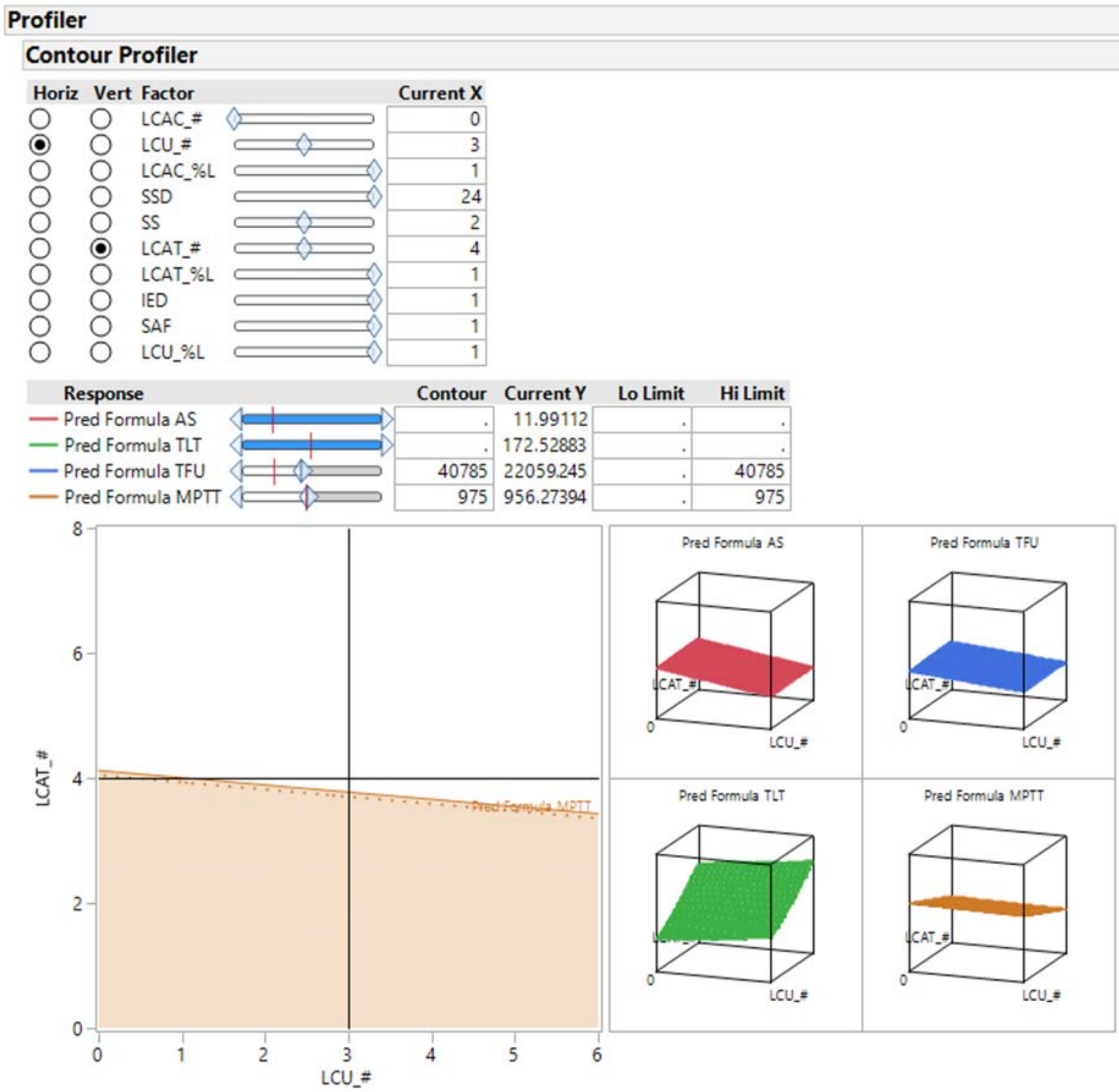

Figure 158. Scenario 25 Solution Space Contour Plot

Scenario #25		
LCU	LCAC	LCAT
3	0	4

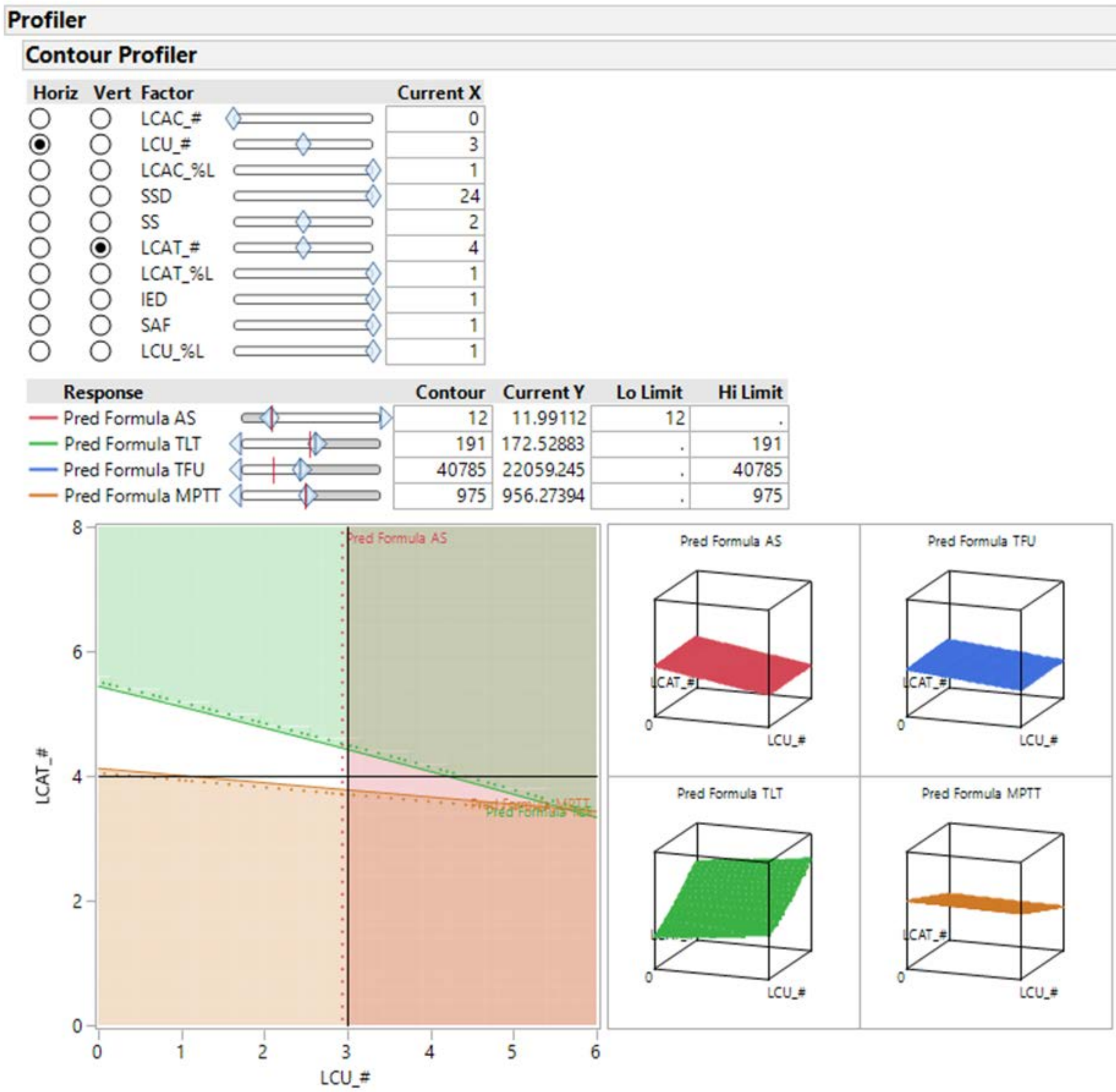

Figure 159. Scenario 25 Solution Space with TLT and AS Contour Plot

Scenario #25		
LCU	LCAC	LCAT
3	0	4

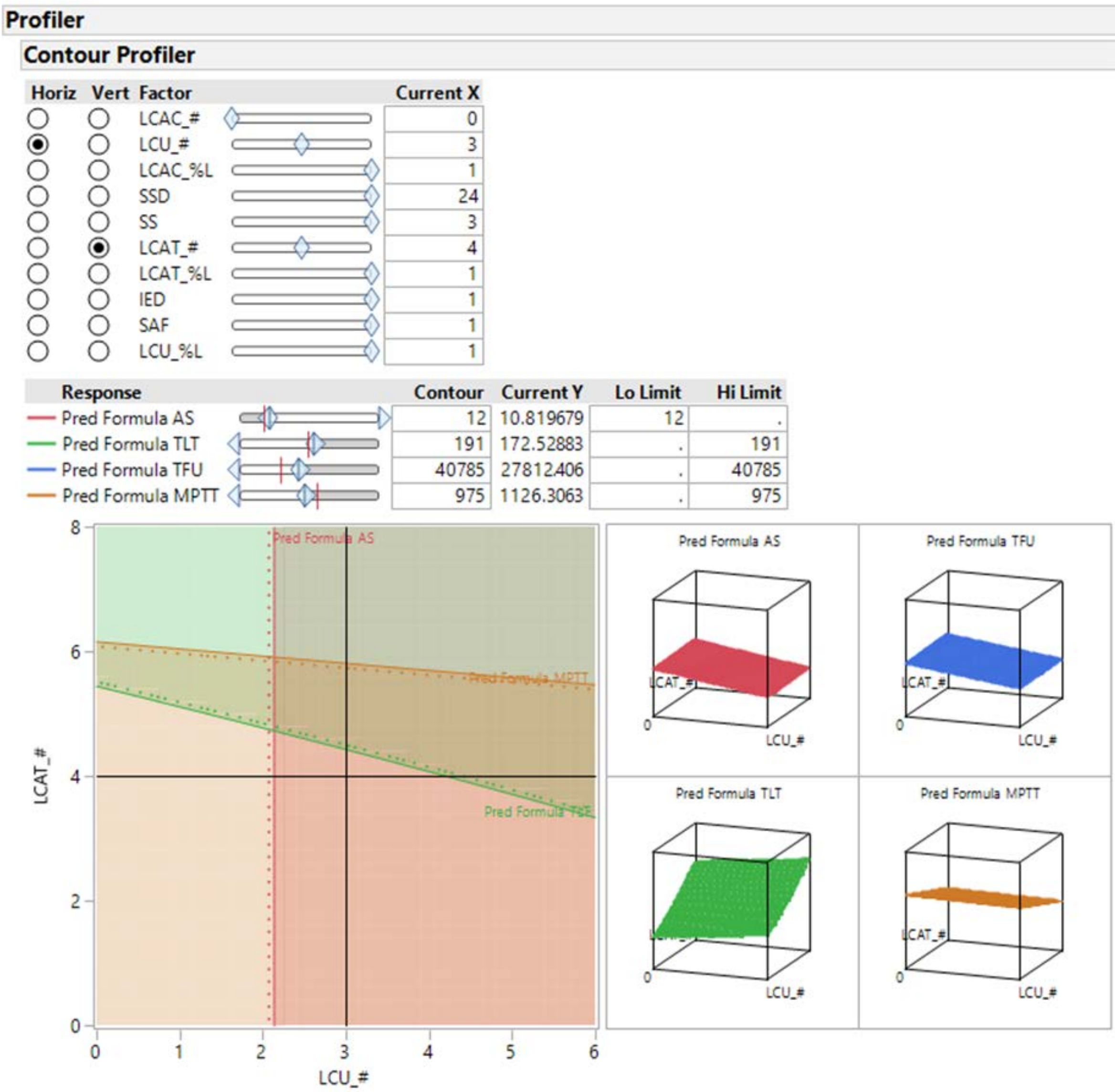

Figure 160. Scenario 25 Limiting Response Contour Plot

Scenario #26		
LCU	LCAC	LCAT
0	4	4

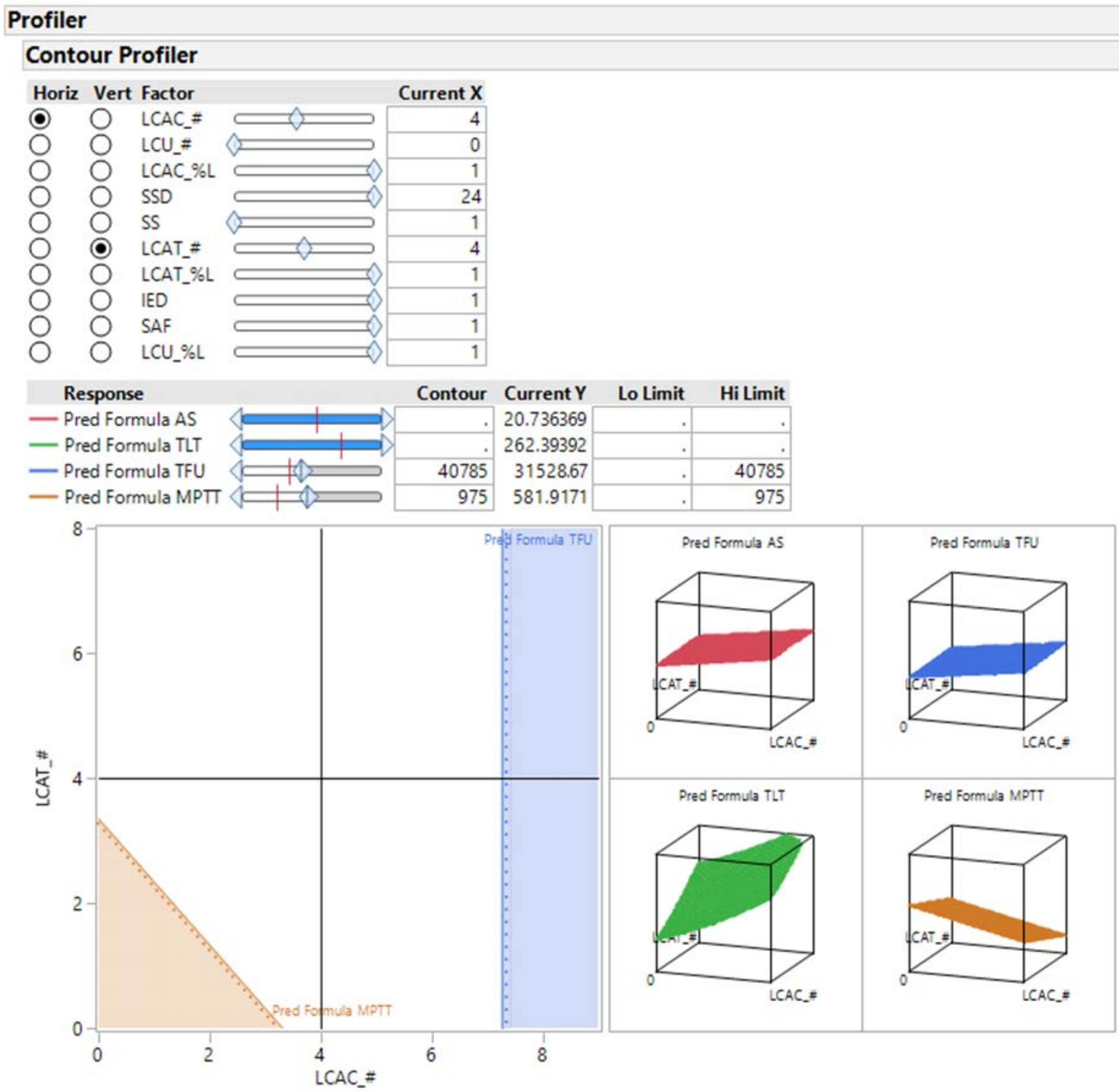

Figure 161. Scenario 26 Solution Space Contour Plot

Scenario #26		
LCU	LCAC	LCAT
0	4	4

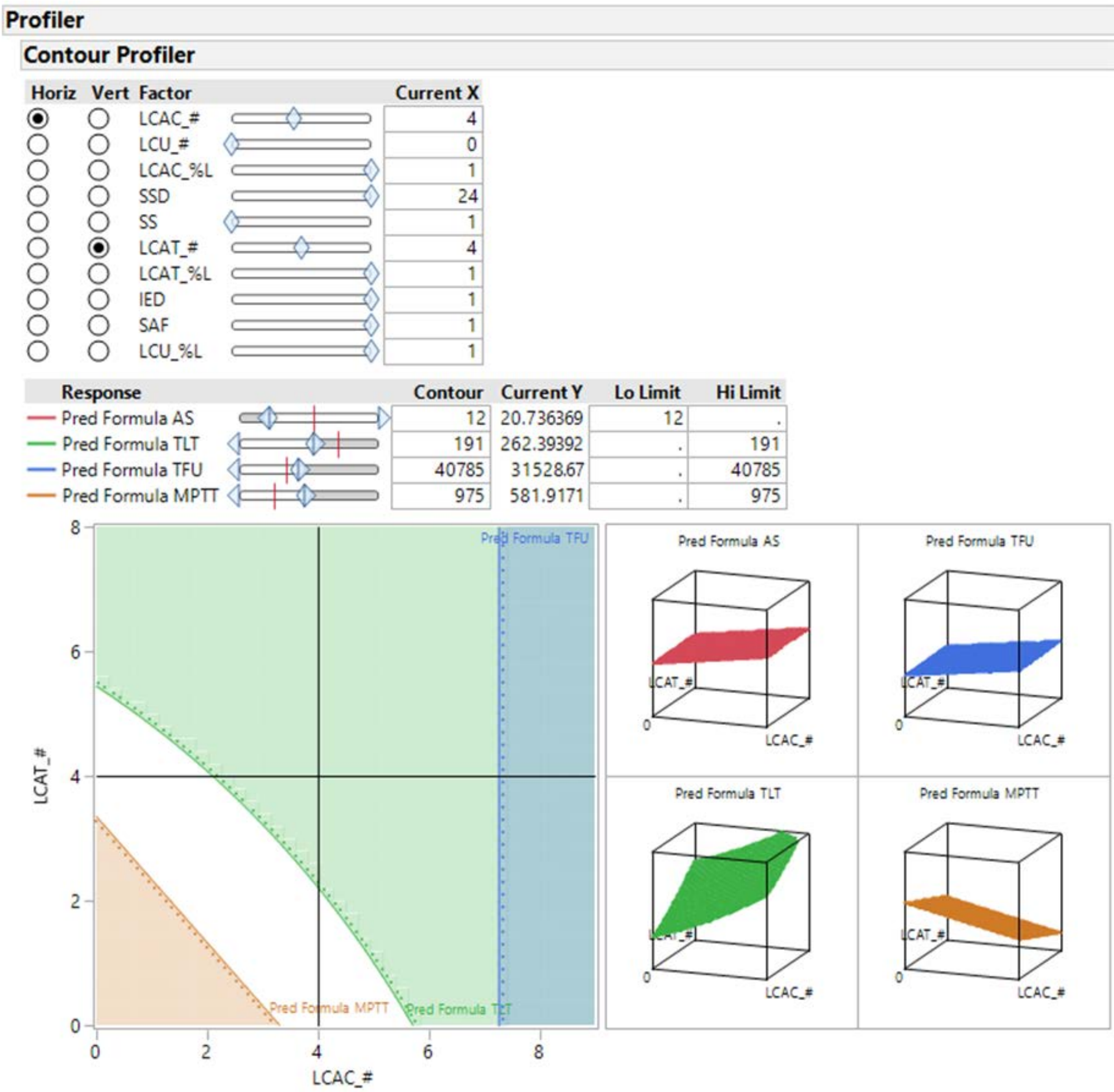

Figure 162. Scenario 26 Solution Space with TLT and AS Contour Plot

Scenario #26		
LCU	LCAC	LCAT
0	4	4

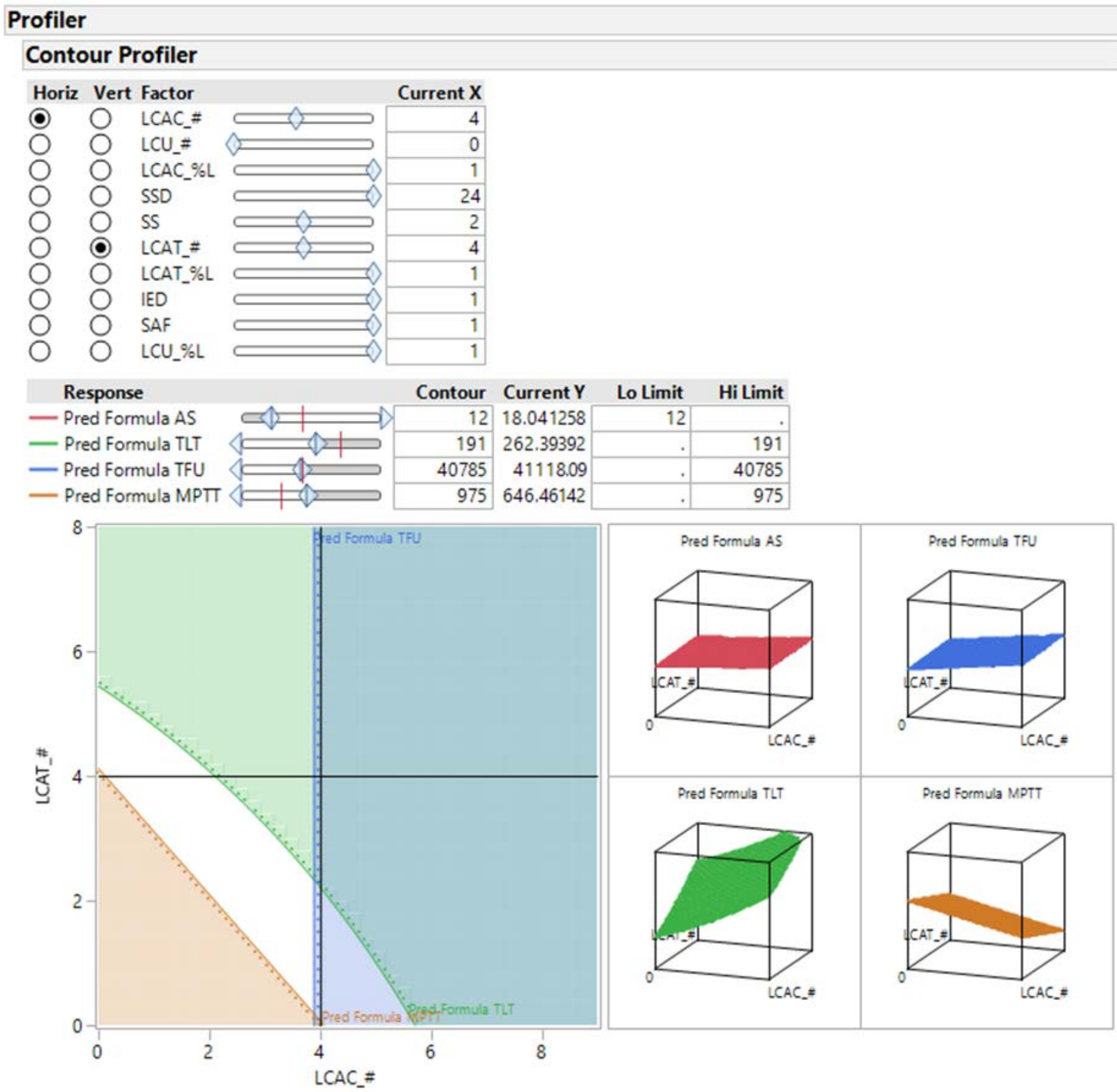

Figure 163. Scenario 26 Limiting Response Contour Plot

Scenario #27		
LCU	LCAC	LCAT
0	0	8

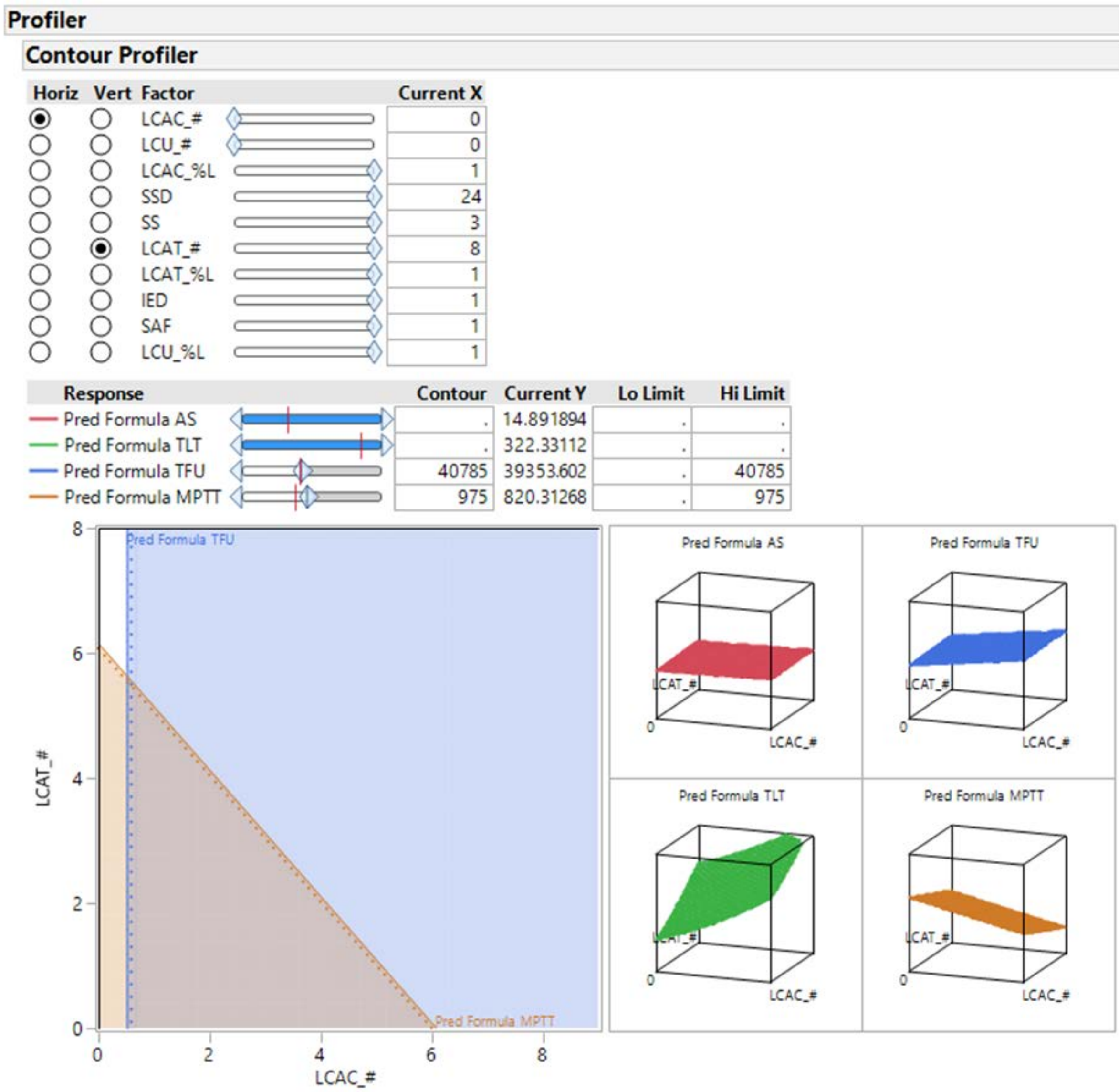

Figure 164. Scenario 27 Solution Space Contour Plot

Scenario #27		
LCU	LCAC	LCAT
0	0	8

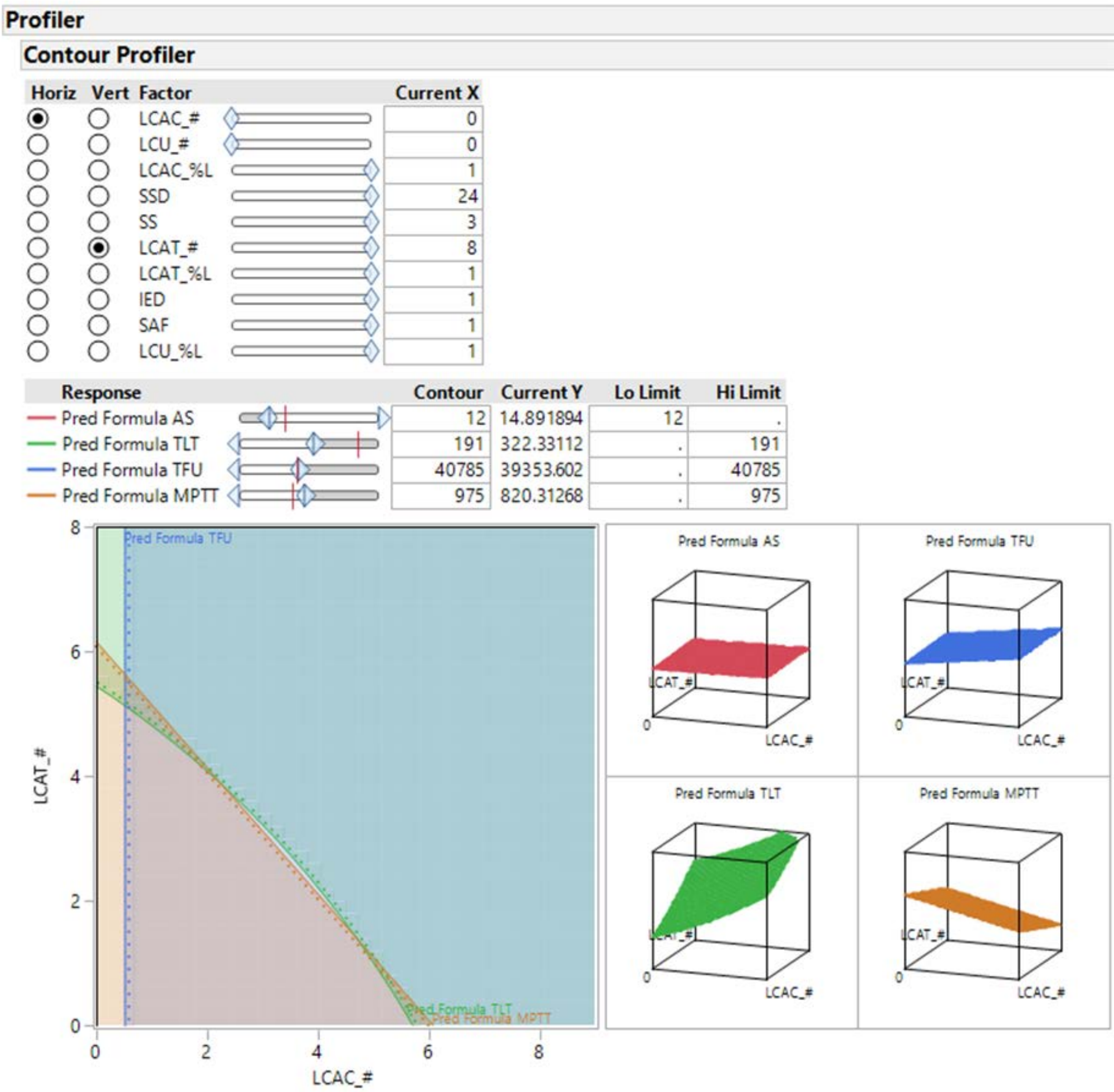

Figure 165. Scenario 27 Solution Space with TLT and AS Contour Plot

APPENDIX I. SCENARIO ANALYSIS

This appendix provides supporting analysis and a figure for the statistical analysis summary of all the contour plots in Appendix G and as discussed in Chapter IV.A.8. Figure 166 details the statistical analysis summary for all scenarios for each response variable. The plot identifies that three scenarios were able to have solution space for all seabase standoff distance (SSD) and sea states (SS) explored in this capstone project. For the other scenarios, column B provides the limiting response for what response, either mission payload transfer time (MPTT) or total fuel used (TFU), limited the solution space. Column C and D identified whether the scenario met the limits when total loiter time (TLT) and average speed (AS) limits were applied.

Scenario Analysis								
Scenario Configuration				A. Maximum Value While Maintaining Operational Effectiveness		B. Limiting Response For A	C. Does the scenario still meet operational effectiveness when limits were added for the following?	
Scenario #	LCU	LCAC	LCAT	SSD	SS		TLT	AS
1	6	0	0	18	2	MPTT	yes	no
2	3	4	0	24	2	MPTT	yes	yes
3	3	0	4	24	2	MPTT	yes	no
4	5	2	0	18	3	MPTT	yes	no
5	2	6	0	24	1	TFU	no	yes
6	2	2	4	24	3		no	yes
7	5	0	1	18	2	MPTT	yes	no
8	2	4	1	24	2	MPTT, TFU	yes	yes
9	0	3	5	24	2	TFU	no	yes
10	4	3	0	24	1	MPTT	yes	yes
11	1	7	0	24	1	TFU	no	yes
12	1	3	4	24	2	TFU	no	yes
13	3	5	0	24	2	MPTT, TFU	no	yes
14	0	9	0	18	2	TFU	no	yes
15	0	5	4	(18, 2), (24, 1)	(18, 2), (24, 1)	TFU	no	yes
16	3	3	1	24	2	MPTT	yes	no
17	0	7	1	(18, 2), (24, 1)	(18, 2), (24, 1)	TFU	no	yes
18	0	3	5	24	2	TFU	no	yes
19	4	0	3	24	1	MPTT	yes	no
20	1	4	3	24	2	TFU	no	yes
21	1	0	7	24	3		no	yes
22	3	2	3	24	2	MPTT	no	yes
23	0	6	3	(18, 2), (24, 1)	(18, 2), (24, 1)	TFU	no	yes
24	0	2	7	24	2	TFU	no	yes
25	3	0	4	24	2	TFU	yes	no
26	0	4	4	24	1	TFU	no	yes
27	0	0	8	24	3		no	yes

Figure 166. Scenario Analysis

APPENDIX J. AHP ANALYSIS

The Analytical Hierarchy Process (AHP) was used when ranking each alternative energy. First the criteria were derived and ranked according to the capstone project effort. Table 15 shows the priority vector calculations as well as the detailed information on how each of the criteria was ranked. The highest vector value was the reliability criteria and lowest was cost. These criteria were selected by the capstone team as the highest interest items for this study.

Table 15. Priority Vector

Criteria Ranking Normalized	Reliability	Power Generation	Maintainability	Supportability	Form Factor	Renewable Energy	Feasibility	Cost	Priority Vector
Reliability	0.368	0.435	0.403	0.355	0.311	0.275	0.246	0.222	33%
Power Generation	0.184	0.218	0.268	0.266	0.249	0.229	0.211	0.194	23%
Maintainability	0.123	0.109	0.134	0.177	0.187	0.183	0.175	0.167	16%
Supportability	0.092	0.073	0.067	0.089	0.124	0.137	0.140	0.139	11%
Form Factor	0.074	0.054	0.045	0.044	0.062	0.092	0.105	0.111	7%
Renewable Energy	0.061	0.044	0.034	0.030	0.031	0.046	0.070	0.083	5%
Feasibility	0.053	0.036	0.027	0.022	0.021	0.023	0.035	0.056	3%
Cost	0.046	0.031	0.022	0.018	0.016	0.015	0.018	0.028	2%

Table 16 shows the calculations that derived the results of the AHP analysis. The factors were derived by obtaining a priority vector for each of the criteria. Each of the criteria was ranked for each system, which produced the compiled table shown. The diesel generator still ends up being the best but renewable energy sources are coming up to speed.

Table 16. AHP Results

Overview of Criteria	Reliability	Power Generation	Maintainability	Supportability	Form Factor	Renewable Energy	Feasibility	Cost	Result
Diesel Generator	0.082	0.076	0.042	0.035	0.020	0.001	0.011	0.010	28%
Wind	0.082	0.028	0.042	0.035	0.007	0.011	0.004	0.004	21%
Solar	0.082	0.010	0.042	0.015	0.020	0.011	0.004	0.004	19%
Flex Gen	0.027	0.076	0.019	0.015	0.020	0.004	0.011	0.004	18%
Wave Attenuator	0.027	0.024	0.005	0.004	0.003	0.011	0.002	0.001	8%
Wave Point Absorber	0.027	0.013	0.005	0.004	0.003	0.011	0.002	0.001	7%

The AHP ranking calculations are shown on the rest of the tables on this section. Each of the criteria was ranked according to each system. The un-normalized tables which are colored show the ranking the capstone team used. The normalized tables show the derivation of the priority vector for the criteria. The compilation of each criterion was shown on the AHP result table. Table 17 through Table 24 show the detailed calculations.

Table 17. Maintainability Ranking Calculations

Maintainability	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	
Diesel Generator	1	3	1	1	7	7	
Flex Gen	0.333333333	1	0.333333333	0.333333333	5	5	
Wind	1	3	1	1	7	7	
Solar	1	3	1	1	7	7	
Wave Point Absorber	0.142857143	0.2	0.142857143	0.142857143	1	1	
Wave Attenuator	0.142857143	0.2	0.142857143	0.142857143	1	1	
Total	3.619047619	10.4	3.619047619	3.619047619	28	28	
Normalized	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	Priority Vector
Diesel Generator	0.276315789	0.288461538	0.276315789	0.276315789	0.25	0.25	0.269568151
Flex Gen	0.092105263	0.096153846	0.092105263	0.092105263	0.178571429	0.178571429	0.121602082
Wind	0.276315789	0.288461538	0.276315789	0.276315789	0.25	0.25	0.269568151
Solar	0.276315789	0.288461538	0.276315789	0.276315789	0.25	0.25	0.269568151
Wave Point Absorber	0.039473684	0.019230769	0.039473684	0.039473684	0.035714286	0.035714286	0.034846732
Wave Attenuator	0.039473684	0.019230769	0.039473684	0.039473684	0.035714286	0.035714286	0.034846732

Table 18. Power Generation Ranking Calculations

Power Generation (kW to support demand)	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	
Diesel Generator	1	1	3	7	7	3	
Flex Gen	1	1	3	7	7	3	
Wind	0.33333333	0.333333	1	3	3	1	
Solar	0.14285714	0.142857	0.333333	1	1	0.33333333	
Wave Point Absorber	0.14285714	0.142857	0.333333	1	1	1	
Wave Attenuator	0.33333333	0.333333	1	3	1	1	
Total	2.95238095	2.952381	8.666667	22	20	9.33333333	
Normalized	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	Priority Vector
Diesel Generator	0.33870968	0.33871	0.346154	0.318182	0.35	0.32142857	0.335531
Flex Gen	0.33870968	0.33871	0.346154	0.318182	0.35	0.32142857	0.335531
Wind	0.11290323	0.112903	0.115385	0.136364	0.15	0.10714286	0.12245
Solar	0.0483871	0.048387	0.038462	0.045455	0.05	0.03571429	0.044401
Wave Point Absorber	0.0483871	0.048387	0.038462	0.045455	0.05	0.10714286	0.056306
Wave Attenuator	0.11290323	0.112903	0.115385	0.136364	0.05	0.10714286	0.105783

Table 19. Supportability Ranking Calculations

Supportability	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	
Diesel Generator	1	3	1	3	7	7	
Flex Gen	0.33333333	1	0.333333	1	5	5	
Wind	1	3	1	3	7	7	
Solar	0.33333333	1	0.333333	1	5	5	
Wave Point Absorber	0.14285714	0.2	0.142857	0.2	1	1	
Wave Attenuator	0.14285714	0.2	0.142857	0.2	1	1	
Total	2.95238095	8.4	2.952381	8.4	26	26	
Normalized	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	Priority Vector
Diesel Generator	0.33870968	0.357143	0.33871	0.357143	0.269231	0.269231	0.321694
Flex Gen	0.11290323	0.119048	0.112903	0.119048	0.192308	0.192308	0.14142
Wind	0.33870968	0.357143	0.33871	0.357143	0.269231	0.269231	0.321694
Solar	0.11290323	0.119048	0.112903	0.119048	0.192308	0.192308	0.14142
Wave Point Absorber	0.0483871	0.02381	0.048387	0.02381	0.038462	0.038462	0.036886
Wave Attenuator	0.0483871	0.02381	0.048387	0.02381	0.038462	0.038462	0.036886

Table 20. Renewable Energy Ranking Calculations

Renewable Energy	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	
Diesel Generator	1	0.142857	0.111111	0.111111	0.111111	0.111111	
Flex Gen	7	1	0.333333	0.333333	0.333333	0.333333	
Wind	9	3	1	1	1	1	
Solar	9	3	1	1	1	1	
Wave Point Absorber	9	3	1	1	1	1	
Wave Attenuator	9	3	1	1	1	1	
Total	44	13.14286	4.444444	4.444444	4.444444	4.444444	
Normalized	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	Priority Vector
Diesel Generator	0.022727	0.01087	0.025	0.025	0.025	0.025	0.022266
Flex Gen	0.159091	0.076087	0.075	0.075	0.075	0.075	0.089196
Wind	0.204545	0.228261	0.225	0.225	0.225	0.225	0.222134
Solar	0.204545	0.228261	0.225	0.225	0.225	0.225	0.222134
Wave Point Absorber	0.204545	0.228261	0.225	0.225	0.225	0.225	0.222134
Wave Attenuator	0.204545	0.228261	0.225	0.225	0.225	0.225	0.222134

Table 21. Reliability Ranking Calculations

Reliability	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	
Diesel Generator	1	3	1	1	3	3	
Flex Gen	0.333333333	1	0.333333	0.333333	1	1	
Wind	1	3	1	1	3	3	
Solar	1	3	1	1	3	3	
Wave Point Absorber	0.333333333	1	0.333333	0.333333	1	1	
Wave Attenuator	0.333333333	1	0.333333	0.333333	1	1	
Total	4	12	4	4	12	12	
Normalized	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	Priority Vector
Diesel Generator	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Flex Gen	0.083333333	0.083333	0.083333	0.083333	0.083333	0.08333333	0.083333333
Wind	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Solar	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Wave Point Absorber	0.083333333	0.083333	0.083333	0.083333	0.083333	0.08333333	0.083333333
Wave Attenuator	0.083333333	0.083333	0.083333	0.083333	0.083333	0.08333333	0.083333333

Table 22. Feasibility Ranking Calculations

Feasibility	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	
Diesel Generator	1	1	3	3	7	7	
Flex Gen	1	1	3	3	7	7	
Wind	0.333333333	0.333333	1	1	3	3	
Solar	0.333333333	0.333333	1	1	3	3	
Wave Point Absorber	0.142857143	0.142857	0.333333	0.333333	1	1	
Wave Attenuator	0.142857143	0.142857	0.333333	0.333333	1	1	
Total	2.952380952	2.952381	8.666667	8.666667	22	22	
Normalized	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	Priority Vector
Diesel Generator	0.338709677	0.33871	0.346154	0.346154	0.318181818	0.31818182	0.334348
Flex Gen	0.338709677	0.33871	0.346154	0.346154	0.318181818	0.31818182	0.334348
Wind	0.112903226	0.112903	0.115385	0.115385	0.136363636	0.13636364	0.12155
Solar	0.112903226	0.112903	0.115385	0.115385	0.136363636	0.13636364	0.12155
Wave Point Absorber	0.048387097	0.048387	0.038462	0.038462	0.045454545	0.04545455	0.044101
Wave Attenuator	0.048387097	0.048387	0.038462	0.038462	0.045454545	0.04545455	0.044101

Table 23. Form Factor Ranking Calculations

Form Factor (Weight and Size)	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	
Diesel Generator	1	1	3	1	7	7	
Flex Gen	1	1	3	1	7	7	
Wind	0.333333	0.333333	1	0.333333	3	3	
Solar	1	1	3	1	7	7	
Wave Point Absorber	0.142857	0.142857	0.333333	0.142857	1	1	
Wave Attenuator	0.142857	0.142857	0.333333	0.142857	1	1	
Total	3.619048	3.619048	10.66667	3.619048	26	26	
Normalized	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	Priority Vector
Diesel Generator	0.276316	0.276316	0.28125	0.276316	0.269231	0.269231	0.274776
Flex Gen	0.276316	0.276316	0.28125	0.276316	0.269231	0.269231	0.274776
Wind	0.092105	0.092105	0.09375	0.092105	0.115385	0.115385	0.100139
Solar	0.276316	0.276316	0.28125	0.276316	0.269231	0.269231	0.274776
Wave Point Absorber	0.039474	0.039474	0.03125	0.039474	0.038462	0.038462	0.037766
Wave Attenuator	0.039474	0.039474	0.03125	0.039474	0.038462	0.038462	0.037766

Table 24. Cost Ranking Calculation

Cost	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	
Diesel Generator	1	3	3	3	7	7	
Flex Gen	0.3333333	1	1	1	3	3	
Wind	0.3333333	1	1	1	3	3	
Solar	0.3333333	1	1	1	3	3	
Wave Point Absorber	0.1428571	0.333333	0.333333	0.333333	1	1	
Wave Attenuator	0.1428571	0.333333	0.333333	0.333333	1	1	
Total	2.2857143	6.666667	6.666667	6.666667	18	18	
Normalized	Diesel Generator	Flex Gen	Wind	Solar	Wave Point Absorber	Wave Attenuator	Priority Vector
Diesel Generator	0.4375	0.45	0.45	0.45	0.38888889	0.38888889	0.427546
Flex Gen	0.1458333	0.15	0.15	0.15	0.16666667	0.16666667	0.154861
Wind	0.1458333	0.15	0.15	0.15	0.16666667	0.16666667	0.154861
Solar	0.1458333	0.15	0.15	0.15	0.16666667	0.16666667	0.154861
Wave Point Absorber	0.0625	0.05	0.05	0.05	0.05555556	0.05555556	0.053935
Wave Attenuator	0.0625	0.05	0.05	0.05	0.05555556	0.05555556	0.053935

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